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Volume I. Project Summary

Arthur D Little , Inc, Cambridge, Mass

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THE IMPACT OF LEAD ADDITIVE REGULATIONS ON THE PETROLEUM REFINING INDUSTRY: VOLUME I - PROJECT SUMMARY

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The report assesses the impact on the U. S. petroleum refining industry of two EPA regulations promulgated to control the level of lead additives in motor gasoline. The first of these regulations requires the availability of low octane, unleaded gasoline for vehicles equipped with lead sensitive catalytic converters. For health reasons, the second regulation requires a gradual phase-down of the lead content of the total gasoline pool (including higher octane gasoline to satisfy the remaining higher compression ratio engines). The report assumes essentially a 100 percent need for unleaded gasoline by 1985. Computer models representative of specific refineries in six geographical regions of the U. S. were developed as the basis for determining the impact on the existing refining industry. New refinery construction during the period under analysis (1975-1985) was considered by development of separate computer models rather than expansion of existing refineries. These models were utilized to assess investment and energy requirements to meet each lead regulation. A sensitivity study was made of the impact on the refining industry of manufacturing a higher octane unleaded gasoline than currently mandated. Other sensitivity studies evaluated the effects of a higher demand for unleaded gasoline than now forecast and of variations in the type of imported crude oil available in the future for domestic refining.

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EPA COMMENT

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In 1974, the Environmental Protection Agency commissioned Arthur D. Little, Inc. to mathematically model the petroleum refining industry in the United States and to predict up to 1985 the impacts on the industry of the entry into the market of unleaded gasoline and the phase-down of total lead use in the gasoline pool. When the study was initiated, Arthur D. Little was given certain baseline assumptions by EPA. These assumptions, which included projections of crude slate, crude supply, product demand, growth rates and gasoline pool characteristics, were made based on the information available at that time. Because of uncertainties with regard to such fundamental questions as future motor vehicle design, emission standards, petroleum supplies and demands, and other factors, the assumptions made for this study generally reflected a somewhat conservative view.

The Environmental Petroleum Agency strongly believes that this study by Arthur D. Little represents a significant step forward in analyses of the refining industry. However, in reviewing the final report, EPA identified certain aspects of the report which should be further clarified to ensure proper interpretation.

First, for the purposes of this study, it was assumed that essentially all gasoline would be the unleaded grade in 1985. Although factors such as average car life and off-highway gasoline use indicate some leaded gasoline will still be required in 1985, there is much uncertainty surrounding this issue, and the conservative decision was made to assume all unleaded gasoline in 1985.

Second, an average product demand growth rate of two percent per year through 1985 was assumed. This does not completely coincide with some opinions concerning improved engine efficiencies in the future. However, the decision was made again on the side of conservatism.

Third, ADL used 1975 dollars in their calculations, whereas other recent studies[1,2] have generally used 1974 dollars. ADL's assumption yields final investment figures 10 to 15 percent higher than the others.

Fourth, it was assumed that unleaded gasoline would be manufactured at about 92 Research Octane Number (and at an 84 Motor Octane Number minimum), instead of the mandated 91 RON, to provide a margin of safety. Some investigators contend that this is a cost of doing business not ascribable to the lead regulations.

Finally, ADL has taken a relatively pessimistic view of the costs of upgrading existing catalytic reformers. The conclusion was based on extensive industry contact. Although EPA does not totally agree with this conclusion, we support ADL's decision.

In light of the above, the reader is cautioned to view the final results of the report in the context of the assumptions that were made.

References

1. EPA-230/3-76-004, Economic Impact Of EPA's Regulations on the Petroleum Refining Industry, April 1976.

2. Draft Report, The Economic Impact of Environmental Regulations on the Petroleum Industry - Phase II Study, Battelle Columbus Laboratories for the American Petroleum Institute, June 11, 1976.

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THE IMPACT OF LEAD ADDITIVE REGULATIONS ON THE PETROLEUM REFINING INDUSTRY: VOLUME I - PROJECT SUMMARY

by

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Prepared for

ENVIRONMENTAL PROTECTION AGENCY
Office of Air and Waste Management
Office of Air Quality Planning and Standards
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May 1976

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Publication No. EPA-450/3-76-016-a

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The report assesses the impact on the U. S. petroleum refining industry of two EPA regulations promulgated to control the level of lead additives in motor gasoline. The first of these regulations requires the availability of low octane, unleaded gasoline for vehicles equipped with lead sensitive catalytic converters. For health reasons, the second regulation requires a gradual phase-down of the lead content of the total gasoline pool (including higher octane gasoline to satisfy the remaining higher compression ratio engines). The report assumes essentially a 100 percent need for unleaded gasoline by 1985. Computer models representative of specific refineries in six geographical regions of the U. S. were developed as the basis for determining the impact on the existing refining industry. New refinery construction during the period under analysis (1975-1985) was considered by development of separate computer models rather than expansion of existing refineries. These models were utilized to assess investment and energy requirements to meet each lead regulation. A sensitivity study was made of the impact on the refining industry of manufacturing a higher octane unleaded gasoline than currently mandated. Other sensitivity studies evaluated the effects of a higher demand for unleaded gasoline than now forecast and of variations in the type of imported crude oil available in the future for domestic refining.

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I. EXECUTIVE SUMMARY

A. INTRODUCTION

This report summarizes a study performed for the Environmental Protection Agency, which was part of a three-phase program undertaken in parallel using a similar conceptual approach and data base. The other two studies are entitled, "The Impact of Producing Low-Sulfur, Unleaded Motor Gasoline on the Petroleum Refining Industry" and the "The Impact of SO_x Emissions Control on the Petroleum Refining Industry," published as EPA report numbers EPA-450/3-76-015a,b and EPA-600/2-76-161a,b, respectively. Significant synergy of data gathering,scenario development, computer simulation time and subsequent analysis was achieved by performing the three separate studies as part of an integrated work program. However, the combined cost implementing all three regulations cannot be obtained by direct summation of the result of the three individual reports.

Initial work on this program began in late 1973. An interim Phase I report was published in May, 1974, entitled "Impact of Motor Gasoline Lead Additive Regulations on Petroleum Refineries and Energy Resources - 1974 - 1980, Phase I", EPA report number 450/3-74-032a. In this Phase I study, the U.S. refining industry was simulated as a single composite model which allowed a rapid overview analysis, but lacked in the desired level of precision.

Accordingly, a more detailed simulation of the U.S. refining industry was developed via a "cluster" model approach which was used in this three-phase effort. This project included collection and collation of an extensive base of refinery data supplied by the Bureau of Mines and individual oil companies, which was used to achieve satisfactory calibration of the cluster models. It is felt that the development and calibration of the cluster models represent a significant achievement in the area of refinery simulation.

In the present report, several scenarios are developed to describe how the petroleum refining industry will likely operate for the next decade, in turn considering manufacture of unleaded gasoline and then the manufacture of unleaded gasoline with a phased reduction in the lead additive content of the total gasoline pool. The report then summarizes the detailed planning assumptions required to execute the program, along with the methodology used to develop these assumptions. The primary study results are then presented herein, defining the impact of lead regulations in terms of capital investment requirements, increased refining costs per gallon of unleaded gasoline, and energy penalties. A complete presentation of planning assumptions, calculational methods, and study results is contained in the appendices of Volume II of this report.

B. SCOPE AND APPROACH

The objective of this study is to determine the impact on the petroleum refining industry of (a) manufacture of unleaded gasoline to meet projected demands, with no lead additive restrictions on the total gasoline pool, and (b) similar manufacture of unleaded gasoline, but with the phased reduction of lead additive content on the total gasoline pool.

The specific goals of the study are to determine for the period through 1985 the impact of these motor gasoline lead additive regulations in terms of (a) capital investment requirements; (b) composite increase in refining costs per gallon of unleaded gasoline, including return on capital, manufacturing cost, and yield losses; (c) increased crude oil requirements; and (d) net energy penalties, reflecting increased crude requirements less the heating value of an increase in the production of refinery byproducts such as liquefied petroleum gases (LPG).

In the study, limitations of present and future refinery configurations are taken into consideration. However, considerations outside the scope of the study include availability of capital requirements, impact upon the competitive structure of the industry, ability of the construction industry to meet the associated refinery construction needs, and costs of distribution and marketing of unleaded or low lead gasoline. The study focused upon the large, complex refineries processing about three-fourths of the crude oil refined in the United States. The impact upon the small refineries comprising over half of the number of U.S. refineries has not been fully assessed. On a relative basis, the penalties to the small refiner probably exceed those reported herein.

In approaching this problem, it was recognized that there are many complex interactions in the petroleum refining industry. Also, there is a necessity for compromises between various process routes for making unleaded or low lead gasoline, including consideration of their capital investments and manufacturing costs. Therefore, a standard analytical tool of the petroleum industry was applied to this problem, computer refinery model simulation with an associated linear programming (L.P.) optimization algorithm. This provided an assessment of the impact of the motor gasoline lead additive regulations with an optimal, minimal cost selection of processing and blending schemes to achieve this end.

Although this analytical method has been used by the petroleum industry for more than a decade for studies of individual refineries, its use in simulation of the entire U.S. refining industry has been limited. Therefore, one of the requirements of this program was the development of a methodology for industry-wide simulation, collection and utilization of data base to confirm the utility of this methodology, and definition of a means to utilize model results to determine national implications of a proposed policy. Equally important was the careful assessment of the planning assumptions regarding the constraints which may be imposed on the petroleum refining industry over the next decade. In all of these activities, Arthur D. Little, Inc., cooperated extensively with representatives of the Environmental Protection Agency and with members of a task force comprised of representatives of the American Petroleum Institute (API) and the National Petroleum Refiners Association (NPRA). As a result of these efforts the utility of the model in faithfully representing the likely behavior of the petroleum refining industry over the next decade was greatly enhanced.

The modeling approach developed in this study provided for a specific simulation of the existing U.S. refining industry, processing domestic crude oils, including Alaskan North Slope crude oil, to the extent available. Any additional crude oil required to meet petroleum product demand was assumed to be imported. Two simulation models, called "grassroots models," were developed to provide for any new refining capacity which would be required to meet product demands in 1980/1985. The grassroots model for the western U.S. used North Slope crude oil, whereas a separate grassroots model for the eastern U.S. used imported oil.

The existing U.S. refining industry was simulated by six individual computer models, constructed to represent clusters of three refineries each in six geographical areas of the United States. These cluster models, therefore, represented refineries typical of the refining industry in terms of crude oil type, processing configuration, and product slate. They ranged in crude oil capacity from 48,000 to 350,000 bbls/day. To ensure that the cluster models adequately represented the industry, an extensive data base on these 18 refineries was collected and analyzed. Processing yield and property data were assimilated to ensure adequate representation of the refinery processes and blending operations. Finally, each cluster model was calibrated by comparison to the extensive data base.

In addition, a methodology for scaling up the results of the cluster models to the entire United States was developed, including these 18 cluster model refineries as well as atypical refineries. In a comparison with 1973 Bureau of Mines data, the most recent year for which complete information was available, the total petroleum products output and crude oil consumption predicted by the model agreed with Bureau of Mines data within 2%. This scale up technique allows assessment of the national impact for the four specific goals of the present program, including an estimate of the impact on small refiners.

Several planning assumptions were required; each of these required auxiliary studies of considerable detail, because of the importance of these planning assumptions to the study results.

Since the impact of motor gasoline lead additive regulations is dependent on the nature of the crude oil being refined, a separate study was made to determine the types of crude oils to be processed by the U.S. refining industry over the next decade. Estimates of domestic crude oil availability were made, including quantity and dispostion of Alaskan North Slope and offshore fields. Also, estimates of world-wide crude oil production and disposition were made, taking into account future product demand in Europe, Japan and the United States in terms of product type and sulfur level requirements. Likely production rates from the North Sea, OPEC countries, and Far East countries, including China, were included in this analysis, as was the likely availability of non-oil energy sources such as coal and nuclear power. When more than one future scenario for the next decade was likely, sensitivity studies were included in the current program to determine the effect of this uncertainty on the study results.

Since the cost of the motor gasoline lead additive regulations depends directly upon the demand for unleaded gasoline and indirectly upon the demand for other petroleum products, a separate forecast was made of petroleum product supply/demand for the next decade. This forecast included an evaluation of the demand for products by individual end-use sector, including the effects of non-petroleum energy sources, conservation, import levels, expanded petrochemical demand for certain products, and the future course of governmental regulation in improving energy self-sufficiency for the U.S. Because of the uncertainties in this, sensitivity studies were included to ensure that these uncertainties did not influence study results.

The impact of any potential regulation also depends upon certain key product specifications on the primary product under control as well as other major refinery products. Present and possible future octane requirements on unleaded gasoline were evaluated. Projections were also made of the future sulfur level requirements of residual fuel oil. To assist in this evaluation, field interviews were conducted with East Coast utilities, accounting for over 90% of the utility fuel oil consumption on the East Coast. Again, certain sensitivity studies were required to define the effects of uncertainties in projections on the study results.

Several other significant assumptions were made in the execution of this program, discussed in detail in the following report.

C. CONCLUSIONS

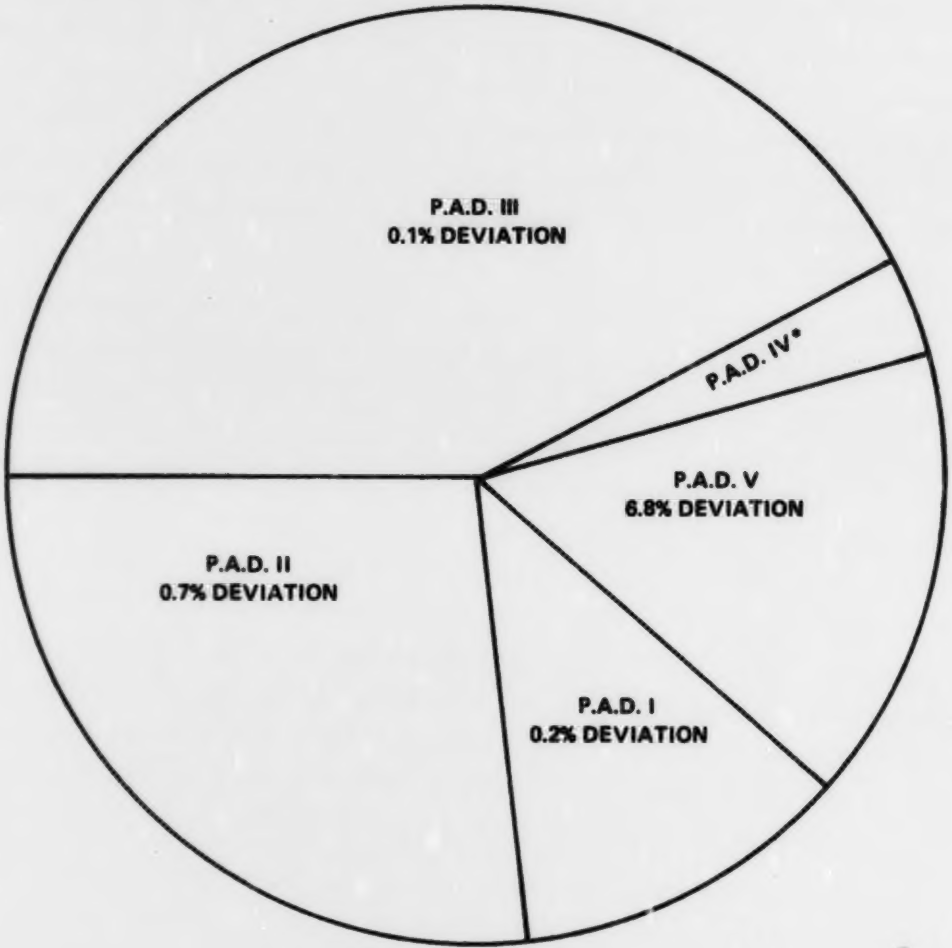
1. Calibration Summary

In order to simulate the existing U.S. petroleum industry, six cluster models were developed to describe the regional characteristics of the refining industry and the processing configurations typical of the industry. Each of these six cluster models represented a cluster of three similar, existing refineries in the United States.

A critical component of the model development was to ensure that these models effectively represented the refineries as well as the section of the United States containing the refineries. Therefore, an extensive calibration effort was undertaken by Arthur D. Little, Inc., in collaboration with the representatives of the Environmental Protection Agency (EPA) and a task force of the American Petroleum Institute/National Petroleum Refiners Association.

Data on raw material intake, fuel consumption, and product outturns for each of the refinery clusters and for the regions of the U.S. containing these clusters were furnished by Bureau of Mines. Proprietary operating data on these refineries were compiled and combined for each cluster by representatives of the EPA. Processing information was obtained from sources in the petroleum industry. Using this processing information the individual cluster models were run on the computer, and compared with the industry data. This task was continued until each cluster model was calibrated with the industry data.

The results of these calibrated cluster models were then scaled up to determine the accuracy with which the refining districts in the U.S. were described. In Figure 1 is shown the deviation of the model predictions from the total raw material intake for the several Petroleum Administration for Defense (PAD) districts in the U.S. As noted therein, the maximum deviation was 6.8% (PAD V), and the deviation from the total U.S. raw material intake was 1.0%. PAD IV (less than 5% of U.S. crude oil capacity) was not simulated by a cluster model, but was included in the scale up method. Thus, as a result of this extensive calibration effort, the cluster models demonstrate an excellent ability to simulate the existing



U.S. Total Deviation = 1%
*Not simulated, but included in scale-up

FIGURE 1. AGREEMENT OF MODEL PREDICTION WITH 1973 B.O.M. TOTAL REFINERY RAW MATERIAL INTAKE DATA
(Area on chart represents percentage of total U.S. refinery intake by P.A.D. District)

U.S. petroleum refining industry, using processing information describing individual refinery units.

2. Qualitative Study Results

If lead is removed from gasolines traditionally manufactured in the United States, the resulting gasoline pool would have a research octane number (RON) of approximately 88 and a motor octane number (MON) of about 80. To provide an unleaded gasoline with a minimum RON of 92 and a minimum MON of 84, the U.S. refining industry must manufacture gasoline with clear (unleaded) octane numbers about four numbers higher than when manufacturing leaded gasoline.

This increased octane is achieved primarily by upgrading existing low severity (lower octane level) reformers to operate at high severity (higher octane level) and by building new high severity reformer capacity. However, there are penalties associated with high severity operation compared to low severity operation. High severity operation does not yield as much gasoline, so additional crude oil is required to produce a fixed volume of gasoline. An increase in clear RON is not matched by a number for number increase in clear MON, so the clear MON specification becomes limiting. This results in clear RON octane "giveaway", i.e., production of gasoline with a higher clear RON than required to meet minimum RON specifications. Finally, the combination of yield loss and the limiting MON specification markedly increases capital investment and operating costs to produce a fixed volume of gasoline.

Other octane boosting processes such as isomerization and alkylation are also used to boost the gasoline pool octane, but these processes contribute in a smaller fashion.

3. Economic Penalties

There are two promulgated regulations on lead usage addressed in this study (Federal Register, January 10, 1973; December 6, 1973). One requires unleaded gasoline to be available for cars requiring it, i.e., those equipped with catalytic converters for emissions control. The other requires that the use of lead in the total gasoline pool (leaded and unleaded combined) be phased down to no more than 0.5 gm/gal by January 1, 1979.

Two external forces, then, are driving the refiner in his usage of lead additives. The phase down regulation places precisely timed limits on total lead usage, although there is still flexibility regarding the quantity of lead the refiner can use in each grade of gasoline. The unleaded gasoline regulation is not nearly so precise, depending upon automobile manufacturers' use and market demand for automobiles equipped with the catalytic converter. The study assumed 2 percent unleaded gasoline sales prior to the 1975 model year introduction, virtually complete use of the converter starting with the 1975 model year and a transition to a total gasoline pool consisting solely of unleaded gasoline by 1985.

Obviously, there is an overlap in the two regulations, because the introduction of converter-equipped cars using unleaded gasoline will influence the lead level of the total pool by reducing total lead usage. The present study does not attempt to define the impact of the phase down regulation alone, without the simultaneous introduction of unleaded gasoline. Instead, the base scenario assumed no lead regulations were imposed (Scenario A); this was then compared to a Scenario B in which only unleaded gasoline regulation was imposed. Finally, the unleaded gasoline regulation and the phase down regulation were simultaneously imposed (Scenario C), for comparison to Scenario B (unleaded gasoline regulation alone imposed). In general, it is not possible to combine these comparative results to determine the impact of some new combination of these two lead additive regulations which has not been discussed herein.

The economic impact on the U.S. refining industry of lead additive regulations is shown in Table 1. By 1985, when the gasoline pool is 100% unleaded, the capital required to make unleaded gasoline is 5.7 billion dollars. This capital requirement includes costs for utilization and upgrading of existing capacity as well as construction of new capacity. Taking into account the timing of investments and the forecasted inflation rates in refinery construction, the ultimate capital requirement will be about 15 billion dollars for unleaded gasoline. The additional refining cost, including capital charges and manufacturing costs, is 1.7 cents per gallon of unleaded gasoline, relative to the average pool of leaded gasoline of Scenario A and first quarter 1975 costs.

Table 1. ECONOMIC IMPACT OF LEAD ADDITIVE REGULATIONS

Economic Impact	Unleaded gasoline[a]			Unleaded gasoline with lead phase down[b]	
	1977	1980	1985	1977	1980
Cumulative capital required—billions of dollars					
Non-inflated (1Q 1975 basis)	0.2	1.8	5.7	1.4	1.7
Inflated	0.3	3.5	14.9	1.9	3.3
Total economic penalty					
Cents per gallon of unleaded gasoline (1Q 1975 basis)	0.13	0.61	1.71	–	–
Cents per gallon of total gasoline pool (1Q 1975 basis)	–	–	–	0.49	0.52

[a] Unleaded gasoline relative to total leaded gasoline pool.

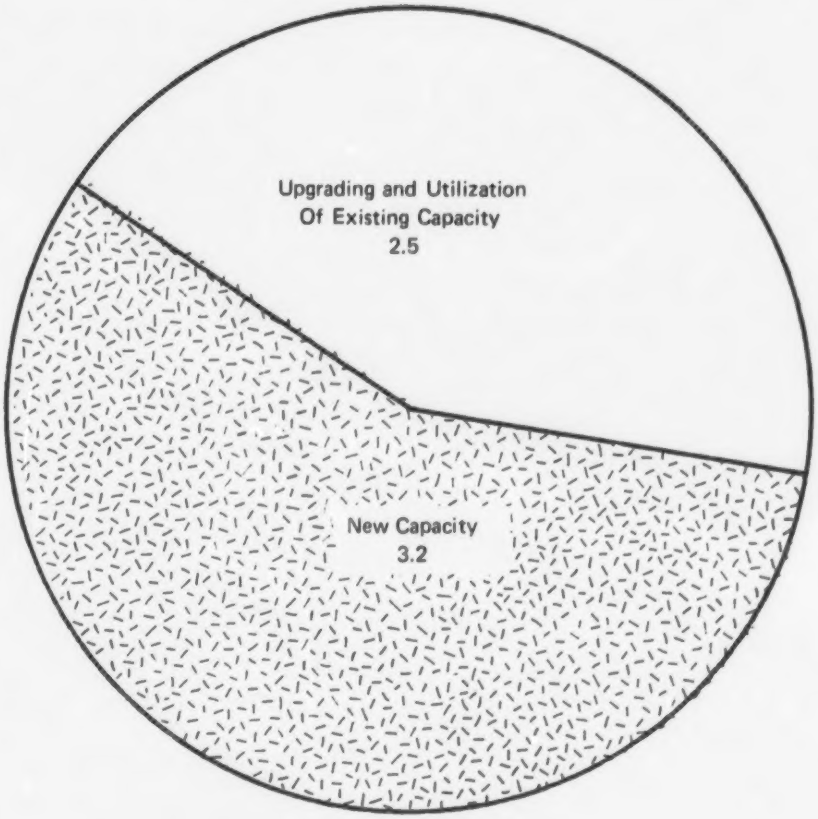
[b] Lead phase down with unleaded gasoline relative to unleaded gasoline without phase down.

If the phase down of lead additives in the total gasoline pool is superimposed upon the introduction of unleaded gasoline, the effect is to change the schedule of capital investment requirements. In 1977, production of unleaded gasoline would require $0.2 billion; superimposing lead phase down would add an incremental $1.4 billion over Scenario B. By 1980, cumulative investment for unleaded gasoline would be $1.8 billion, and superimposing lead phase down would add an incremental $1.7 billion. By 1985 there is no incremental penalty over Scenario B for lead phase down, since all gasoline produced is unleaded. Thus, total cumulative investment to manufacture unleaded gasoline will be $5.7 billion by 1985 whether or not lead phase down is introduced. It can therefore be seen that the primary impact of lead phase down is on the timing of capital outlays and not on total cumulative investment.

In Figure 2 is shown the components of the cumulative capital requirement for unleaded gasoline manufacture by 1985. Approximately 40% of the investment is required for capacity upgrading and 56% is required for additional new capacity in both existing refineries and new grassroots refineries.

Figure 3 shows the estimates of the economic penalty associated with the manufacture of unleaded gasoline in 1977, 1980, and 1985, and breaks down the cost into capital charge, operating costs, and crude and product penalties. This illustrates a somewhat lower cost in 1977 and 1980 because unleaded gasoline has been obtained to some extent by selective product blending. However, by 1985 when 100% unleaded gasoline production was assumed, the full cost of unleaded gasoline emerges.

These estimates have been based on the scale up of the results from eight different refinery LP models which blended the unleaded gasoline to exactly 92/84 RON/MON. They therefore represent estimates of the economic penalties for manufacturing gasolines with average octane numbers of 92/84 RON/MON, and do not represent the penalties for manufacturing gasolines with a minimum specification of 92/84 RON/MON. However, such average specifications well represent the average octane of currently produced unleaded gasoline.



Total = 5.7 Billion Dollars

FIGURE 2 CAPITAL INVESTMENT REQUIRED BY 1985 TO MANUFACTURE UNLEADED GASOLINE (TOTAL USA) BILLIONS DOLLARS (1Q 1975 BASIS)

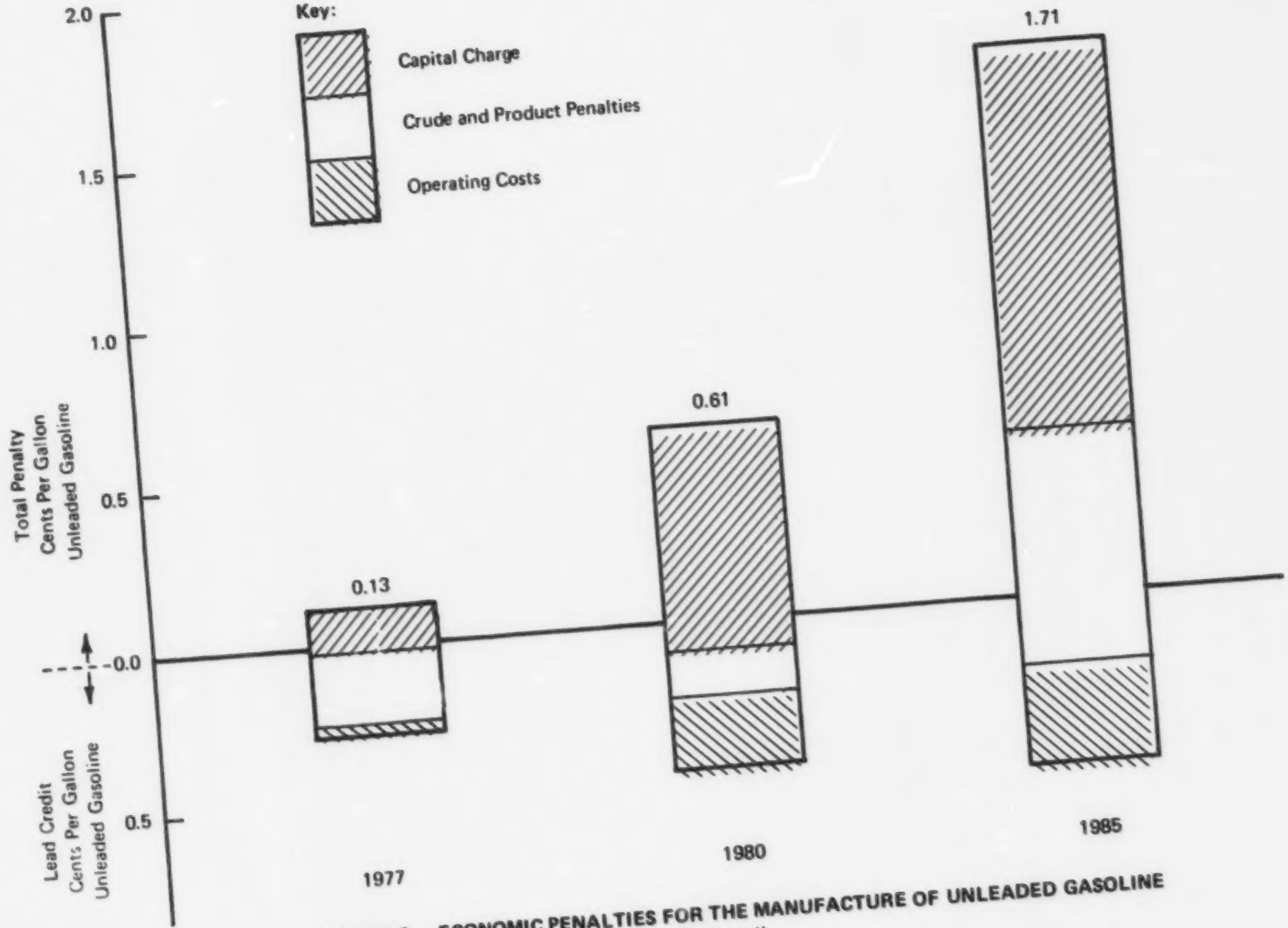


FIGURE 3 ECONOMIC PENALTIES FOR THE MANUFACTURE OF UNLEADED GASOLINE
(relative to total leaded gasoline pool)

4. Crude Oil and Energy Penalties

The estimates of the crude oil and net energy penalties due to imposition of lead additive regulations are shown in Table 2. By 1985 it is estimated that the U.S. refining industry will have to process additional crude oil in excess of 250,000 barrels per day to manufacture unleaded gasoline, relative to the production of the leaded pool of Scenario A. However, the industry would produce more LPG as a result, which would partially offset this crude oil penalty. The net energy penalty by 1985 is estimated to be 180,000 barrels per calendar day of fuel oil equivalent for the manufacture of unleaded gasoline, relative to the production of a leaded pool (Scenario A).

In 1980, the production of unleaded gasoline requires an additional 60,000 BPD of crude oil, relative to production of leaded gasoline. The superimposition of the lead phase down regulation will require an additional 55,000 BPD of crude run over Scenario B, which assumes only the unleaded gasoline regulation is in effect. Net energy penalties for these cases are, respectively, 20,000 BPD and 35,000 BPD. Since the gasoline pool is 100% unleaded in 1985, there are of course no energy penalties for the superimposed lead phase-down regulation.

5. Sensitivity Studies

A number of sensitivity studies were conducted and two of these indicated potential uncertainties which could significantly increase the cost of lead regulations above those reported for the base case, described above.

Some observers believe that higher octane gasoline may be needed for some automobiles fueled by unleaded gasoline as these automobiles accumulate mileage. This has been termed "octane requirement increase" (O.R.I.). The determination of the O.R.I. is beyond the scope of the present study, but several model runs were undertaken to determine the impact on the petroleum refining industry should increased octanes be required.

As already mentioned, the RON/MON specification of 92/84, used for the base case studies discussed above, adequately represents the unleaded gasoline currently being produced. As shown in Table 3, a sensitivity

Table 2. CRUDE OIL AND ENERGY PENALTIES FOR LEAD ADDITIVE REGULATIONS

	1977	1980	1985
Unleaded gasoline[a]			
Additional crude oil required thousands barrels per calendar day	19.9	60.1	255.5
Additional LPG produced thousands barrels per calendar day	6.0	56.1	92.5
Net energy penalty thousands barrels per calendar day of fuel oil equivalent	14	20	180
Lead phase down[b]			
Additional crude oil required thousands barrels per calendar day	73.7	54.6	–
Additional LPG produced thousands barrels per calendar day	47.7	25.5	–
Net energy penalty thousands barrels per calendar day of fuel oil equivalent	38	35	–

[a] Unleaded gasoline relative to total leaded gasoline pool.

[b] Lead phase down with unleaded gasoline relative to unleaded gasoline without lead phase down.

study was directed at assessing the cost of producing unleaded gasoline with an RON/MON of 93/85. This increased the total capital required for producing unleaded gasoline by 1.2 billion dollars (20%), on a first quarter 1975 cost basis. Hence, the total investment requirement was increased to 6.9 billion dollars and the economic penalty to 2.1 cents per gallon of unleaded gasoline, relative to the leaded pool of Scenario A. The ultimate investment and economic penalty will be markedly higher, due to inflation in refinery construction costs, as illustrated in Table 1.

An additional study was conducted with an RON/MON specification of 94/86, but the model experienced great difficulty in producing unleaded gasoline at this higher octane specification. It is quite possible that the model may not adequately represent the octane producing capability of the individual refiner in this range of gasoline specifications, leading to an understatement of his capabilities. If industry-wide octane specifications of 94/86 (RON/MON) were needed, further studies of refining industry capabilities should be undertaken.

Some observers have argued that the necessary use of unleaded gasoline to meet automotive emission standards has led to changes in engine design which provide inferior mileage. This contention has been debated for some time and cannot be resolved here. However, to analyze the impact of such a circumstance, a sensitivity study was carried out in which the unleaded gasoline demand in 1985 was increased by 5% over the baseline projection. As shown in Table 3, under this condition, the investment required to produce unleaded gasoline is thereby increased to 7.1 billion dollars (25% increase) on a first quarter 1975 cost basis, and the economic penalty is increased to 2.1 cents per gallon unleaded gasoline, relative to the leaded pool. Again, the ultimate investment and economic penalty will be markedly higher, due to the effects of inflation in refinery construction costs.

Table 3. RESULTS OF SENSITIVITY STUDIES FOR LEAD ADDITIVE REGULATIONS

		Sensitivity studies[a]	
	Base Case	Higher RON/MON	Greater demand
Unleaded gasoline RON/MON	92/84	93/85	92/84
Ex-Refinery gasoline demand, MB/CD	8,041	8,041	8,427
Capital investment			
Billions dollars (1Q 1975 basis)	5.7	6.9	7.1
Economic penalty			
Cents per gallon of unleaded gasoline (1Q 1975 basis)	1.71	2.10	2.08[b]

[a] Unleaded gasoline relative to total leaded gasoline pool.

[b] Becomes 3.4 cents with increased crude oil to meet incremental gasoline demand.

6. Other Major Implications

The choice of six different cluster models to represent the existing U.S. refining industry was made to provide a reasonable representation of the different types of refineries operating today. Over 80% of U.S. refining capacity has been represented in the cluster models. However, no cluster model was constructed which could be considered representative of the small refiner (less than 50,000 barrels per day), nor would such a model be sufficient to a study of the impact on small refiners. These refiners represent less than 20% of total U.S. refining capacity and any understatement of their penalties will not significantly affect the overall conclusions. However, the lead additive regulations could have a significant impact on the smaller refiner. He does not have the wide choice of blending components available to the larger refiners. Also, because of the economies of scale the unit cost to the small refiner of meeting lead additive regulations will be higher than those indicated in this study. This could have a significant impact on the competitive structure of the refining industry.

Since the total gasoline pool is projected to be unleaded by 1985, the primary impact of lead phase down in these studies is to accelerate the investment requirements rather than to add to them. In Figure 4 are shown the capital requirements in each study period for producing unleaded gasoline with and without a superimposed lead phase down regulation. The investment credits show in 1985 with lead phase down reflect this accelerated investment schedule; more investment is required in 1977 and less in 1985.

With the lead phase down schedule assumed in this study (and in effect in 1974), the 1977 investment requirement is increased from 0.2 billion dollars to 1.4 billion dollars as a result of lead phase down alone. The bulk of this investment is required for upgrading and utilization of existing catalytic reforming capacity, but a significant fraction of this investment has already been made. Hence, these incremental costs due to lead phase down do not solely represent new capital construction projects required by 1977 but rather total accumulated

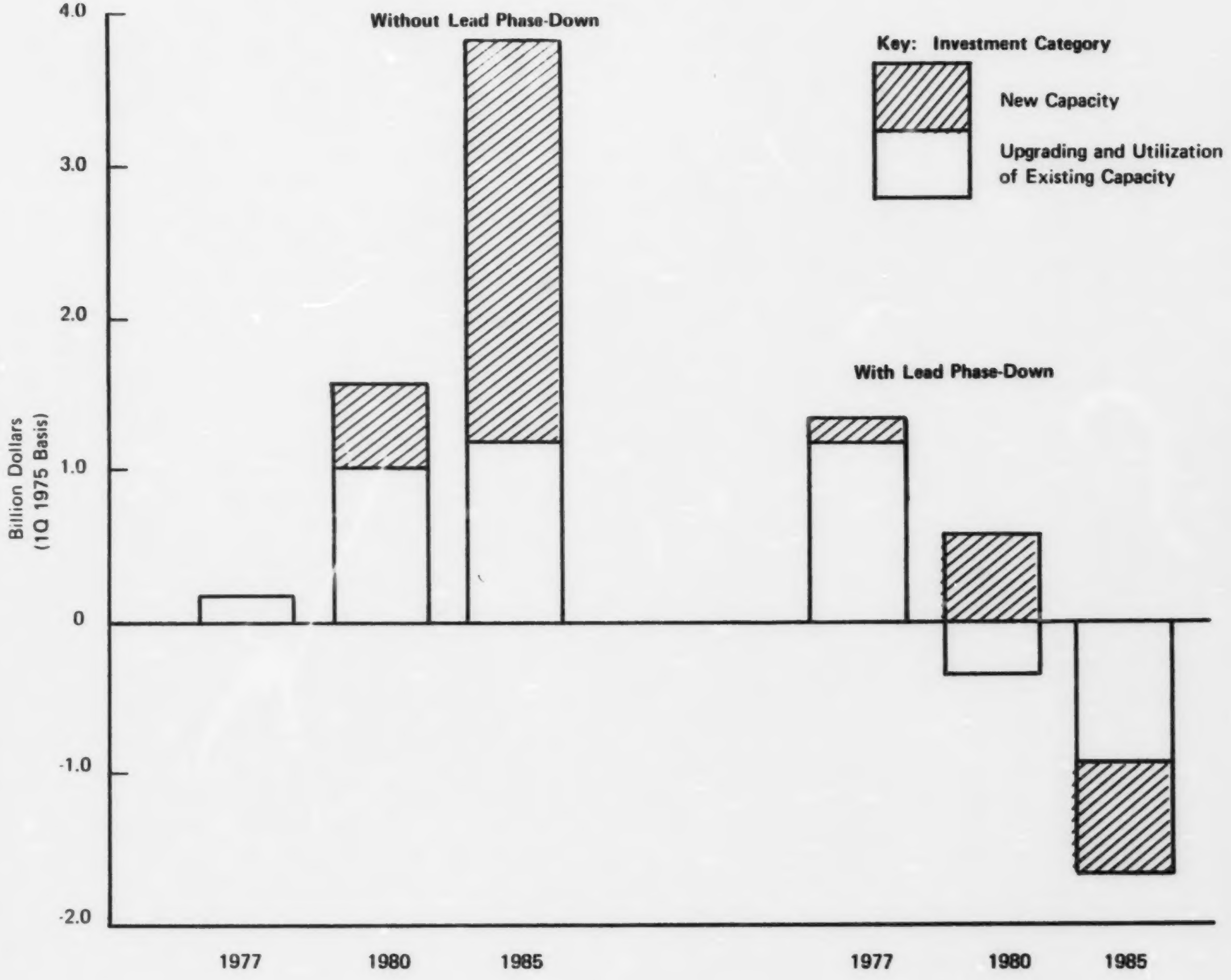


FIGURE 4 IMPACT OF THE INTRODUCTION OF LEAD PHASE-DOWN ON THE TIMING OF CAPITAL INVESTMENT REQUIREMENTS TO MANUFACTURE UNLEADED GASOLINE

investments through 1977. No assessment has been made of new construction projects required by 1977.

Finally, the results of the sensitivity studies should be reemphasized, for these indicate a possible increased penalty of 20-25%, should either increased unleaded gasoline octane or increased gasoline consumption be required.

D. RECOMMENDATIONS FOR FURTHER ACTION

In order to assess more fully the impact of lead additive regulations, three areas are worthy of more consideration than possible with this study:

1. A more definitive survey should be made of the octane producing capability of the existing U.S. refining industry. This factor is highly important both in assessing the economic impact of lead additive regulations and in determining the capability of the industry to react to increased octane requirements of unleaded gasoline.
2. The impact of lead additive regulations should be assessed more fully for the small refiners processing less than 50,000 barrels per day. Such studies should examine the economic impact on the refiners as well as the likely effect on the competitive structure of the industry.
3. Studies should be conducted of interactions of lead additive regulations and other environmental regulations applicable to the petroleum industry. The investigation should include examination of possible processing changes which are required to meet lead additive regulations but which are precluded by other environmental regulations.

II. STUDY BASIS

A. APPROACH

The objective of this study is to determine the impact on the petroleum refining industry of promulgated Environmental Protection Agency (EPA) regulations requiring the manufacture of unleaded gasoline and the phased reduction of lead in the gasoline pool, taking into consideration limitations of present refinery configuration and potential grassroots refining construction. Since the processing interactions in any single refinery are exceedingly complex, and indeed even more complex for the industry as a whole, such an assessment of the impact of lead regulations could be addressed by two possible approaches.

First, a survey could be conducted by sending out a questionnaire[1,2] to individual refiners across the country, requesting an assessment of their individual costs for meeting the regulation. The results could then be composited to define the cost to the industry. Although this is a valid approach, it is often difficult to determine if the specific regulation is being interpreted equivalently by all refiners across the country, if they are using a similar analytical procedure, if they are using the most efficient means of meeting the regulation, and if they are using a common basis for cost estimation. This method, however, does have the decided attribute of allowing each individual refiner to assess his unique problems in meeting the regulation.

An alternative approach, used in the present study, is to simulate the U.S. refining industry using computer models. Computer simulation of individual refineries is well-known and has been practiced over a decade. Such a simulation normally utilizes a linear programming (L.P.) model to represent the individual process units and the process interactions of the refinery. In the present study, however, simulation of a single refinery is not sufficient in that no single refinery can be said to represent the entire refining industry. Therefore, eight computer models were used simulating individual refineries which, when composited, would be typical of the industry as a whole.

In the use of any L.P. model it is necessary to define the types of crude oils available to the model, the individual process yields, the streams that can be used to connect the processes, and the products produced from the refinery. The model then uses an optimization algorithm to select the optimal combination of process units meeting the objective of the study. If all product prices are given as input to the model, the model will select that set of product outturns and processing configurations which will maximize profit derived from the complex. However, this method of L.P. optimization may not assure that the quantities of products being produced from the complex meet the product demands of the region being served by that refinery. If this happened in the actual operation of the refinery, market forces would increase the prices of those products in short supply and decrease those in excess supply, so that the entire refinery operation would be adjusted with the product outturns just meeting the product demands. In a computer simulation of a refining industry, however, it is very difficult to predict those product prices which are required to match the product outturns with the market demands. In the present studies, an alternate approach was taken, wherein the product outturns from the refinery were fixed in order to meet the projected product demands imposed upon the U.S. refining industry. Therefore, the L.P. algorithm selected a set of processing configurations which allowed this specified product demand to be met at minimum cost. However, it is necessary that the problem being optimized be carefully constructed such that the real-world constraints on the industry in meeting these minimum cost objectives would be met, allowing a realistic simulation of the operation of the industry. The definition and inclusion of these constraints is an exceedingly important component of a study of the impact of any regulation on the industry. This activity was greatly benefited by the results of a Federal Energy Administration/National Petroleum Refiners Association conference on refining industry modeling.[3]

In order to meet the constraints which would be imposed upon the refining industry, comprised of nearly 300 individual refineries spread throughout the United States, Arthur D. Little Inc. (ADL), representatives of the EPA, and a task force comprised of representatives of the American Petroleum Institute and the National Petroleum Refiners Association selected three refineries in each of six geographic regions to simulate the existing U.S. refining industry. These six refinery models (cluster models) were constructed and calibrated[4] against the three actual refineries in each region to ensure that the product blend flexibility and the processing configuration flexibility did not exceed that available to these refineries. In simulating these existing refineries over the next decade, the crude run for the individual cluster models was not allowed to exceed the crude capacity for those refineries being simulated. All new crude capacity required to meet increased product demand was met by the construction of new, grassroots refineries.

In the construction of new grassroots refineries, the refining industry east of the Rockies was represented by a class of refineries feeding crude oil typical of imported oil likely to be available in the coming decade. Another simulation model was developed for grassroots refineries to be constructed west of the Rockies, feeding Alaskan North Slope crude oil. The product outturn from all of the existing refineries (cluster models) and the new refinery installations (grassroots models) was then composited to ensure that the overall product demand for the United States refining industry was met.

It is also important that the major products of the models meet appropriate quality constraints typical of the product quality demanded by the marketplace over the next decade. In some cases these product quality definitions are implicit in the EPA regulation under study, for example the constraint on the amount of lead additives allowed in the gasoline pool. In other cases, projections of future product quality requirements are necessary in order that the study be a realistic representation of the industry over the next decade. Of particular importance in this regard is the sulfur level of the residual fuel oil being produced by the industry. Separate studies were made of these product qualities to determine the likely levels associated with the industry over the next decade, discussed in the planning assumptions for the study.

The impact upon the refining industry which is evaluated in the present study includes: the capital investment requirements for the refinery to meet the lead regulations, the composite capital charge and operating cost expressed per gallon of unleaded gasoline, the crude oil penalty, and the net energy penalty associated with the regulation (including byproducts which have an energy value).

There are other considerations important to the determination of the impact of the regulation. These other considerations were beyond the scope of the study and have not been evaluated in detail. For example, the study determines the capital outlay required to meet the lead regulations by the industry. However, it is likely that, for many of the small refiners in the country, the projected capital outlay will require financing that may not be available to them at the present time. The availability of capital required by the regulation is specifically beyond the scope of this study, as was the impact of the regulation on the competitive structure of the industry. Also, some of the processing requirements needed to meet the regulation require significant construction of heavy-walled vessels. The impact of the lead regulations upon the construction industry, including the fabricators and vendors, is also not considered to be within the scope of the present study. The impact of the distribution and marketing requirement of the promulgated regulations is also not addressed herein.

B. CASE DEFINITIONS

The cluster model approach used in the present study provides a reassessment of two promulgated regulations (Federal Register, January 10, 1973; December 6, 1973) requiring (1) availability of unleaded gasoline for automobiles with catalytic converters and (2) a phased reduction of the lead content of the total gasoline pool (leaded and unleaded) to a level of 0.5 gm/gal by January 1, 1979. This modeling approach was also used in two related studies of possible regulations requiring reduction of gaseous sulfur-oxide (SO_x) emissions from petroleum refineries and requiring reduction of the sulfur content of unleaded gasoline. To conduct these studies, six scenarios were created as possible modes of operation of the refining industry, each of which were evaluated for 1977, 1980 and 1985. These scenarios are:

Scenario A: Unregulated operation and expansion of refining industry to meet projected petroleum product demand over the next decade.

Scenario B: Manufacture of unleaded gasoline to meet projected demands, with no lead restrictions on the total gasoline pool or sulfur restrictions on unleaded gasoline.

Scenario C: Manufacture of unleaded gasoline to meet projected demands, with phased reduction in the lead additive content of the total gasoline pool and with no sulfur restrictions on unleaded gasoline.

Scenario D: Manufacture of unleaded gasoline with a maximum of 100 ppm sulfur, while reducing the lead content of the gasoline pool.

Scenario E: Manufacture of unleaded gasoline with a maximum of 50 ppm sulfur, while reducing the lead content of the gasoline pool.

Scenario F: Reduction of refinery gaseous sulfur-oxide emissions by restrictions on the sulfur content of the refinery fuel, by restriction of fluid catalytic cracker plant emissions, and by restriction of sulfur recovery (Claus) plant emissions, while meeting all the requirements of Scenario C.

The complete definition of the computer cases to be run under these several scenarios requires assumptions of crude intakes to the U.S. refinery industry, processing configurations, and product outturns and qualities. However, other planning assumptions which have a possibility of occurring over the next decade were also considered. Variations in these assumptions were investigated by a series of parametric runs, wherein the assumptions were modified, one at a time, to reassess the impact on the industry. The scope of these parametric studies is summarized in Table 4.

For the study of lead in gasoline (Scenarios A, B, and C) five major parametric studies were undertaken. A basic premise of the study in the base case is that unleaded gasoline will be produced by the industry meeting 92 Research Octane Number (RON) and 84 Motor Octane Number (MON). These specifications were set one octane number higher than the minimum required by the EPA regulation to allow for refinery blending margin. To evaluate the effect of producing even higher octane unleaded gasoline, two

Table 4 . PARAMETRIC STUDIES

Lead in gasoline	Low sulfur unleaded gasoline	Refinery sulfur oxide emissions
Unleaded gasoline RON/MON = 93/85	Residual fuel oil Sulfur level projection	Variation in imported crude slate
Unleaded gasoline RON/MON = 94/86	Variation in imported crude slate	Residual fuel oil, sulfur level projection
Residual fuel oil sulfur level projection	Sulfur distribution around FCC unit	Stack gas scrubbing
Variation in product demand	Method of FCC gasoline desulfurization	
Variation in imported crude slate		

parametric runs were conducted considering two levels of higher octane for the unleaded gasoline as summarized in Table 4.

Projections of the future sulfur content of residual fuel oil consumed in the United States are between 1.1 and 1.4%. As a base planning assumption, it was considered that the residual fuel oil being consumed in the United States would have a sulfur content of approximately 1.3%. Since this requires extensive desulfurization in the new grassroots refinery facilities, an additional parametric run at 1.1% sulfur was conducted to ensure that study results were not being unduly influenced by this assumption. It must be emphasized, of course, that the average sulfur level of the fuel oil consumed by all sectors in the United States is below even 1.1%, because of significant levels of imports of low-sulfur fuel oil into the United States over the next decade.

In the base case studies defined by the above scenarios, it was assumed that all petroleum products would grow at a level of 2% per annum. This is a reasonable estimate of the growth of all petroleum products.[5] However, it is likely that each individual product will not grow at 2% per annum, so parametric runs were undertaken to evaluate the impact of growth rates for petroleum products other than 2%.

Arthur D. Little, Inc., has conducted a worldwide survey of crude oil production and disposition to the various refining regions. This indicated that two alternatives might be considered for the imported crude oil into the East Coast region: (1) the imported oil could be of relatively high-sulfur content characteristic of Arabian crudes, or (2) the imported oil may be of relatively lower sulfur level, characteristic of Nigerian crudes. There is great uncertainty as to the demand and availability of various crude oils in the United States[6] and the ultimate selection of crude oils would depend upon this uncertain demand as well as a variety of political factors. The base case under the above scenarios assumed a predominantly Arabian-type imported oil. An additional parametric run was made with a lower-sulfur oil being characteristic of the imported oil.

In the program to evaluate the impact of a reduction of sulfur levels in unleaded gasoline a similar set of parametric studies were required. As indicated in Table 4, projections of the refinery residual fuel oil sulfur level and variations in imported crude slate, discussed above, were also considered.

The attention of the refinery industry to sulfur levels in gasoline in general has been minimal over the last few decades because of the relative lack of importance of sulfur level as a product specification. Therefore, there is limited information available regarding the sulfur level of some of the high sulfur gasoline blend components from the various refinery processes under various conditions of operation. One of the most critical refinery units with regard to the sulfur content of unleaded gasoline is the fluid catalytic cracker (FCC). Sulfur levels of the products from the FCC unit were obtained by consideration of available data on the FCC unit, feeding various types of gas oil and under various types of operating conditions. However, since there are uncertainties in the sulfur content of gasoline from FCC units, a parametric run was instituted to evaluate the impact of higher levels of sulfur in the FCC gasoline than was assumed in the base case scenarios above. This, then, led to a range of potential impact on the petroleum industry in consideration of both the base case sulfur level as well as the new parametric case sulfur level.

Because the interest in the sulfur content of FCC gasoline has been recent, the most efficient means of desulfurizing FCC gasoline has not been determined. One attractive method of reducing the sulfur level in the FCC gasoline is by hydrotreating the FCC feedstock. Another method is to directly desulfurize FCC gasoline, requiring further reforming of the desulfurized product. However, laboratory data has shown that the sulfur distribution in FCC gasoline is heavily weighted toward the heavy gasoline component. This suggests that only the heavy gasoline component need be directly desulfurized, with the light FCC gasoline component going directly into the gasoline blend stock. This method of desulfurization of FCC gasoline could potentially reduce the impact on the refining industry of meeting the possible sulfur regulation. Consequently, one parametric run was made to determine the possible savings from this method of desulfurizing FCC gasoline.

In the study of the impact of proposed regulations reducing the sulfur oxide emissions from refineries, several parametric studies were also undertaken. Variations in the sulfur level of imported crude slate and sulfur level of the product residual fuel oil are clearly of potential importance in the impact of regulations reducing refinery sulfur oxide emissions. These parametric studies, discussed above, were included in this particular task.

It is felt that the most likely means by which the refining industry will meet possible regulations regarding sulfur oxide emissions is to control the sulfur level of the refinery fuel system, to desulfurize the FCC feedstock (thereby reducing FCC regenerator sulfur oxide emissions), and to add tailgas cleanup processes to the sulfur recovery unit (Claus process). However, it is also possible that the emissions from the FCC unit and the refinery fuel system could be reduced by the utilization of stack gas scrubbing techniques, under extensive study for possible application in the utility industry. Consequently, parametric runs were undertaken to determine if the total impact of the regulations reducing sulfur oxide emissions could be diminished by application of the utility-based stack gas scrubbing techniques.

The present report deals with the impact only of the promulgated regulations reducing the lead additive content of gasoline. Companion reports[7,8] have been produced which address the impact of the reduction of sulfur in unleaded gasoline and the reduction of sulfur oxide emissions from the refinery. All further discussions in the present report will address the promulgated lead reduction regulations.

C. PLANNING ASSUMPTIONS

This subsection defines the methodology used in developing planning assumptions required for the present study, as well as identifying the primary assumptions used. Because of the amount of detail required in presenting these planning assumptions, only an outline of this information will be presented below. Additional detail on all of the topics discussed is presented in the appendices of Volume II of this report.

1. Crude Slate Projections

Projection of the crude slate available for the domestic U.S. refining industry depends upon a complex interaction of the production capability of domestic U.S. crudes, the demand for petroleum products, the influence of alternate energy sources within the U.S., the worldwide availability of crude oils and the demand worldwide for these same international crude oils. Arthur D. Little, Inc., investigated the worldwide oil supply by consideration of production potential from the North Sea, OPEC countries, the United States, South America and the socialist countries. Superimposed upon this production potential was the investigation of world oil demand forecasts and product demand forecasts for the major refining and consuming areas, i.e., the U.S.A., the Caribbean, Western Europe, and Japan. These product demand forecasts indicated, for example, a significant lightening of the future product demand barrel in Europe, a similar but less significant change in Japan, and virtually no change in the relative proportions of demand within the United States. This led to a projection that there would be a tendency for heavier crudes, including Nigerian, to be attracted to the U.S.A. and lighter crudes, including Algerian, to be attracted to Europe. Crude oil demand for Japan included both imports from the OPEC countries as well as probable production of Chinese crude oil. In addition, the demand for sulfur content of various products was investigated, allowing an assessment of the likely movements of crude oils of various sulfur levels into the various consuming regions in the world. The assessment of all these factors in combination allowed projections of the disposition of the various crude oils to the various refining regions.

Superimposed upon any such projection of the availability of crude oils to the United States must be an evaluation of the proportion of the U.S. refineries which can run sweet and sour crudes. Obviously, a refinery designed for sweet crude operation can be redesigned to allow operation with sour crudes, but this would be accomplished only if there is sufficient price driving force between the sweet and sour crudes. For example, the NPRA has evaluated the availability of refineries which depend upon low-sulfur crude oil and have indicated 9% of the refining capacity would be unavailable if the industry were forced to substitute high-sulfur crude oil for 20% of the sweet crude they are now running.[9]

After consideration of all of these factors the planning assumption for the crude oil to be run by the U.S. refining industry over the next decade is summarized in Table 5. Additional detail on the crude oils run

Table 5. U.S. REFINERY CRUDE RUN
(millions of barrels per calendar day)

	1977	1980	1985
Domestic			
Alaskan North Slope	–	1.3	1.5
Other	9.4	9.0	8.5
Subtotal domestic	9.4	10.3	10.0
Domestic, percent of total	70.7%	70.1%	61.0%
Imported			
Arabian	2.1	2.7	4.0
African	0.8	1.3	2.0
South American	0.5	0.4	0.4
Other	0.5	–	–
Subtotal imported	3.9	4.4	6.4
Imported, percent of total	29.3%	29.9%	39.0%
Total crude run	13.3	14.7	16.4

to the refining industry in 1973 as well as the assumptions made in reducing this number of crude oils to a smaller but still descriptive level is contained in Appendices F and I. Additional detail on the methodology utilized to obtain the projected crude run shown in Table 5 is presented in Appendix A.

In addition to the overall crude slate to be processed by the U.S. refining industry, a breakdown between the crudes being processed by existing refineries and those to be processed by new grassroots refineries over the next decade must be specified. As described below, the existing U.S. industry is simulated by means of six cluster models. The cluster models process all available domestic crude over the time span of the next decade and uses imported crude as required to meet overall product demand. In the base case, these imported crudes were assumed to be comprised predominantly of Arabian light crude oil. The grassroots model on the West Coast processes only Alaskan North Slope crude oil, because projections indicate an ample supply of North Slope crude oil to meet the demands of PAD District V. Note, however, that although some published reports[6] indicate an ample supply of North Slope crude oil for PAD District V (even leading to planning for a pipeline transport of excess North Slope oil to the Midcontinent), there is not a consensus among the major U.S. refiners as to whether the North Slope crude will be sufficient to exceed the petroleum product demand in District V.

The crude oil to be processed in the new grassroots refineries east of the Rockies is assumed to be imported oil, predominantly Arabian Light crude oil. However, as noted above, a parametric run was made to investigate the impact of importation of lower sulfur crude oils, such as Nigerian-type oils. This parametric run would also indicate the effect of introduction of Alaskan North Slope crude oil into the Midcontinent, used in new grassroots refinery construction east of the Rockies.

2. U.S. Supply/Demand Projections

Prior to 1973, forecasting the oil demand in the United States was a straightforward exercise, involving the application of historically determined growth rates to base year consumption data. However, the pattern of continuous growth was interrupted by massive increases in foreign oil prices (and later domestic decontrolled prices), the Arab oil embargo, and a period of economic recession.

The general approach which has been used by ADL in product demand forecasting is to conduct an indepth analysis of total energy requirements by individual end-uses, which are then matched with projections of supplies of basic energy sources, including oil, gas, coal, nuclear and hydroelectric power. Because of the stimulus of high oil prices and considerations of security of supply, non-oil energy supplies are developed as rapidly as possible, limited only by technical, environmental, governmental, and resource considerations on the one hand, and by end-use considerations on the other, such as the nuclear contribution being limited to the base load electric power generation. The availability of non-oil energy sources are also evaluated in the light of the recent declines of United States natural gas production, potential environmental constraints on exploitation of coal reserves, inflation-caused reappraisal of the capital intensive new energy forms such as oil shales, and failure to meet targets for nuclear generation capacity. Furthermore, the product demands incorporate recent changes in the structure of energy use within end-use sectors, such as increased electricity consumption in the domestic sector and an increased use of oil as petrochemical feed stock. Also included is the effect of energy conservation. Of course, the impact of energy conservation is difficult to assess from recent product demand data because of the simultaneous occurrence of economic recession, mild winters, and high oil prices.

In the current study the demand forecast for the United States refining industry was obtained by two different approaches. To facilitate the task of combining the demand forecast with the scale up of the cluster models (Appendix G), one simplistic forecasting approach was utilized which led to a growth rate of 2% per annum for all products from the domestic refining industry. However, to ensure that the study results were not unduly influenced by this simplistic approach, parametric runs were undertaken to evaluate the affect of a more sophisticated forecasting technique. Each of these forecasting techniques will be discussed in summary form here, while additional information of a detailed nature is presented in Appendix B.

a. Uniform Product Growth at 2% Per Annum

Since the demand forecasts are intended simply to identify differences in refining requirements among the six scenarios, the actual demand forecast for each product may be relatively unimportant. Therefore, the methodology, discussed in additional detail in Appendix B, contains three key simplifying assumptions: (1) demand for all products grows at one uniform rate of 2% per annum between 1975 and 1985; (2) demand growth occurs in equal increments throughout this forecasting period; and (3) product imports are maintained at 1973 levels.

From the base year, 1973, product demand was forecast to realize zero growth over 1974 and 1975, and average 2% per annum thereafter. Beyond 1975, published projections of oil demand growth rate range between 1% and 3.5% per annum, depending upon assumptions regarding oil prices, consumer price sensitivity, conservation incentives, the availability of alternate energy forms, and U.S. government policy. An estimate of 2% average annual growth was selected to reflect generally slower than historical growth rates resulting from higher oil prices, but assuming some optimism regarding the future economic growth of the country.

It is not likely that this demand forecast will closely approximate the real growth of petroleum products over the next decade; however, this was demonstrated in the present study to be an adequate assumption of this product growth rate. To arrive at this conclusion, parametric runs were made utilizing more detailed evaluations of product demand growth, the methodology for which is discussed below.

b. Non-Uniform Petroleum Product Growth Rates

In this more sophisticated projection of product demand growth rate, two sets of assumptions were used to develop a definitive range of energy supply/demand balances. In one case, economic growth was assumed to be somewhat slower than historical rates, but high enough to permit a rising standard of living. Higher energy prices alone (but not governmental action) are assumed to result in consumer energy conservation. Likewise, higher energy prices provide the incentive for the development of domestic energy resources. A second case was defined in which economic and total energy growth fall further off historic rates as a result of both strong governmental action and higher energy prices. Government action in the form of conservation incentives, selective taxes on oil, import tariffs on oil, etc., is taken to enhance the effects of higher prices in dampening demand and stimulating the development of domestic resources.

In both of these categories, coal production and consumption, which have declined in recent years, are expected to be rejuvenated as a result of higher energy prices. After development of the coal industry, production capacity will no longer be such a severe limitation on coal consumption after 1980. Natural gas is assumed to be supply-constrained throughout the forecast period, as production from the contiguous United States fields continues to decline and is not offset by volumes from Alaskan sources until very late in the forecast period. Nuclear power is expected to be the most rapidly growing primary energy form, showing 25- to 30-fold increase over the forecast period. Nonconventional energy sources, such as solar, are not expected to play a significant role during the time frame of this forecast.

The demand for energy was developed by breaking down the total energy consumption into demand by various end-use sectors (e.g., transportation, industrial, residential/commercial, etc.). At the end-use sector level, the historical growth trends in energy consumption were identified and then modified in line with the basic assumptions described above. The modification of historic growth rates took into account our expectations of the impact of consumer conservation, government policy, energy prices, and macro-economic conditions.

The breakdown of oil demand by product was accomplished by examining the oil consumption patterns of specific end-use sectors. To project future oil consumption patterns in the transportation sector, for example, separate forecasts were developed for automotive, rail, marine, and air transport, and the fuels were projected accordingly, taking into account any efficiency improvements expected.

The product forecast from this analysis is shown in detail in Appendix B. Imported petroleum products were assumed to be held constant in the results of both of these demand forecasts at the 1973 level, as a result of governmental policy considerations. It is therefore possible to compare product imports with the domestic U.S. demand to arrive at the domestic refinery demand for the next decade. These refinery production expectations were used in the LP model studies.

c. Gasoline Grade Distribution

For both of these demand forecasts, it is necessary to project the gasoline grade requirements over the next decade, under the scenarios pertaining to lead regulations. By consideration of the expected growth rate of introduction of new cars (requiring unleaded gasoline), new car imports, and automotive distribution by weight, the grade distribution under these scenarios was projected as defined in Table 6.

3. Key Product Specifications

The definition of future product specifications is quite important to the successful operation of the cluster and grassroots models. For example, in the study of lead regulations on gasoline, if hydrotreating of fluid catalytic cracker (FCC) feed stock is used, the sulfur levels of all of the FCC products would be diminished, including the sulfur level of blending components in the fuel oil pool. To actually represent the cost of lead reduction, therefore, a specification must be placed to prevent the fuel oil pool sulfur level from changing. Hence, in any study of the impact of a regulation on the refining industry, accurate definition of the product specifications for the major petroleum products must be considered in order that the computer model operate in a fashion which would be realistic in terms of petroleum industry flexibility or market demand.

The importance of economic factors in the determination of petroleum product specifications is well known. For example, there is usually a price premium associated with the lower sulfur levels of heavy fuel oil. In addition, there are performance requirements for certain product specifications, such as the distillation and volatility characteristics of motor gasoline. In recent years, however, the impact of governmental regulations on the specifications for petroleum products has become increasingly pronounced, such as a regulation which would specify the lead level of motor gasoline. Hence, an assessment is required of the likely future course of governmental regulations on major products over the next decade.

Table 6. GASOLINE GRADE REQUIREMENTS BY PERCENT

Grade Distribution %	1977					1980					1985					U.S. average		
PAD	I	II	III	IV	V	I	II	III	IV	V	I	II	III	IV	V	1977	1980	1985
A. No lead regulations																		
Premium (100 RON)	27	16	25	13	38	33	22	31	19	44	40	29	38	26	50	24	30	37
Regular (94 RON)	65	76	68	80	52	64	75	67	79	52	58	69	60	72	48	68	68	61
Unleaded (92 RON)	8	8	7	7	10	3	3	2	2	4	2	2	2	2	2	8	3	2
B. Unleaded with no lead phasedown																		
Percent of pool																		
Premium	15	5	13	3	22	4	1	3	1	5	0	0	0	0	0	12	3	0
Regular	54	63	56	66	42	37	39	38	40	31	0	0	0	0	0	56	37	0
Unleaded	31	32	31	31	36	59	60	59	59	64	100	100	100	100	100	32	60	100
C. Unleaded with lead phasedown[a]																		
Promulgated lead phasedown pool average, grams/gal.	1.0					0.5					b					1.0	0.5	b
Allowable grams of lead per gallon of leaded gasoline	1.74					1.66					b					1.74	1.66	b

[a] same distribution pattern used as in unleaded (Item B.)

[b] 100% unleaded gasoline

Complete identification of product specifications in the computer model is contained in Appendix C. The highlights of the analysis and the principal product specifications used are summarized here.

a. Motor Gasoline Specifications

Among the most important product specifications for motor gasoline in such a study is the octane number of the several grades of motor gasoline to be produced from the refining industry. Survey data on the three grades of motor gasoline is shown in Table 7. In the modeling studies of the present investigation, the projected research and motor octane numbers for regular, premium and unleaded gasoline, respectively, over the remainder of the decade varied by region (Appendix C), but were approximately 93/85, 99/91, and 92/84. Some studies[10,11] may be interpreted to indicate that the unleaded gasoline octane numbers shown in Table 7 will be increased over the next decade. Hence, two additional parametric runs were conducted, wherein the research and motor octane numbers of the unleaded gasoline pool were 93/85 and 94/86, respectively.

In Table 8 are shown selected results of a survey on unleaded gasoline, broken down by district. It is apparent that the 92/84 specification on the research and motor octane numbers used in this study describes a large fraction of the United States marketing area, particularly since MON is the limiting specification. The average sensitivity is somewhat larger than used in the present study. This will make the study results conservative in principle; in practice, it will have no effect due to MON being the limiting specification.

The Reid vapor pressure of the gasoline pool, as shown in Table 7, varies significantly between summer operation and winter operation. Previous studies[12] have shown that the summer/winter operation can be effectively simulated by means of an average Reid vapor pressure, reflective of both summer and winter operations. Consequently, in the present program all gasoline specifications were set at 10.5 lbs. RVP.

It has also been reported[13] that realistic distillation specifications on motor gasoline must be used in computer simulations to ensure that the model adequately represents the refining industry. Table 7 provides historical data on distillation specifications for comparison with those placed

Table 7. MOTOR GASOLINE SURVEY DATA

	Grades of motor gasoline				
	Regular		Premium		Unleaded
	Winter 1974-1975	Summer 1974	Winter 1974-1975	Summer 1974	Winter 1974-1975
Research octane no.	93.4	93.4	98.9	98.9	92.3
Motor octane no.	86.1	85.9	91.6	91.5	84.0
Lead, g/gal	1.58	1.90	2.10	2.32	0.02
Reid vapor pressure, lb.	12.0	9.6	11.8	9.7	10.9
Distillation, °F					
20% evaporation	129	142	134	146	139
30% evaporation	152	164	161	172	166
50% evaporation	202	211	210	217	214

Source: U.S. Dept. of Interior, Bureau of Mines, Petroleum Products Survey Motor Gasolines, Summer 1974 and Energy Research & Development Administration, BER C/PPS–75/1 – Motor Gasolines, Winter 1974–75.

Table 8. MOTOR GASOLINE SURVEY, WINTER 1974-75
AVERAGE DATA FOR UNLEADED GASOLINE IN EACH DISTRICT

			Octane number			
District name	Gr., ASTM D287 °API	Sulf., ASTM D1266 wt. %	RON ASTM D2699	MON ASTM D2700	$\frac{R+M}{2}$	RVP, ASTM D323 lb
Northeast	59.2	0.029	92.8	83.9	88.4	11.0
Mid-Atlantic Coast	60.2	.027	92.5	83.8	88.2	11.4
Southeast	59.8	.024	92.5	83.7	88.1	11.0
Appalachian	60.6	.022	92.9	84.5	88.7	11.8
Michigan	61.7	.033	91.9	83.9	87.9	12.1
North Illinois	61.2	.026	92.3	84.3	88.3	12.2
Central Mississippi	62.5	.024	92.0	83.8	87.9	10.9
Lower Mississippi	61.2	.034	92.5	83.8	88.2	11.5
North Plains	63.3	.052	92.0	84.3	88.2	11.1
Central Plains	65.1	.037	92.0	84.3	88.2	10.8
South Plains	63.9	.033	92.0	84.6	88.3	10.8
South Texas	60.6	.019	92.0	83.7	87.9	11.1
South Mountain States	61.9	.038	91.5	83.4	87.5	9.7
North Mountain States	63.8	.033	91.5	83.6	87.6	10.0
Pacific Northwest	61.8	.010	92.7	84.7	88.7	11.0
North California	56.9	.016	93.2	83.9	88.6	9.4
South California	59.0	.044	92.5	83.5	88.0	9.7
Average	61.3	.029	92.3	84.0	88.2	10.9

Source: Energy Research & Development Administration, BER C/PPS–75/1 – Motor Gasoline, Winter 1974-1975.

on gasoline products as follows. For premium gasoline the 150°F distillation temperature is reached between 20 and 28% distilled overhead, and the 210°F distillation temperature is reached between 42 and 54% distilled overhead. With regular and unleaded grades the 150°F distillation point is reached between 20 and 30% distilled overhead, whereas the 210°F specifications were identical to those of the premium grade gasoline.

b. Sulfur Content of Residual Fuel Oils

As indicated above, one of the key product specifications required to ensure that the model approximates realistic operation is the sulfur level of the residual fuel oil. This specification is important because the minimum cost approach of the LP model is to produce higher sulfur fuel oils rather than adding desulfurization and Claus plant investment. This subsection summarizes the methodology and results of our forecast for the U.S. fuel oil demand of differing sulfur contents. Of particular emphasis here is the sulfur level of residual fuel oils produced from domestic U.S. refineries, in contrast to the sulfur level of total U.S. residual fuel oil demand, which is influenced by imported fuel oils.

To determine the allowable sulfur content of fuel oil to be burned as refinery fuel (and not marketed) for each of the cluster models, an evaluation was made of the existing state regulations on allowable SO_x emissions. This analysis included an investigation of the regulations applicable to the particular refineries being simulated in the cluster models as well as those for the PAD district the model was intended to simulate. From this analysis of regulations, sulfur specifications were determined for refinery fuel for each cluster model, ranging from 0.6% to 1.5% depending on the geographical location of the cluster model simulation. A complete discussion of the methodology and results of this analysis is presented in Appendix D.

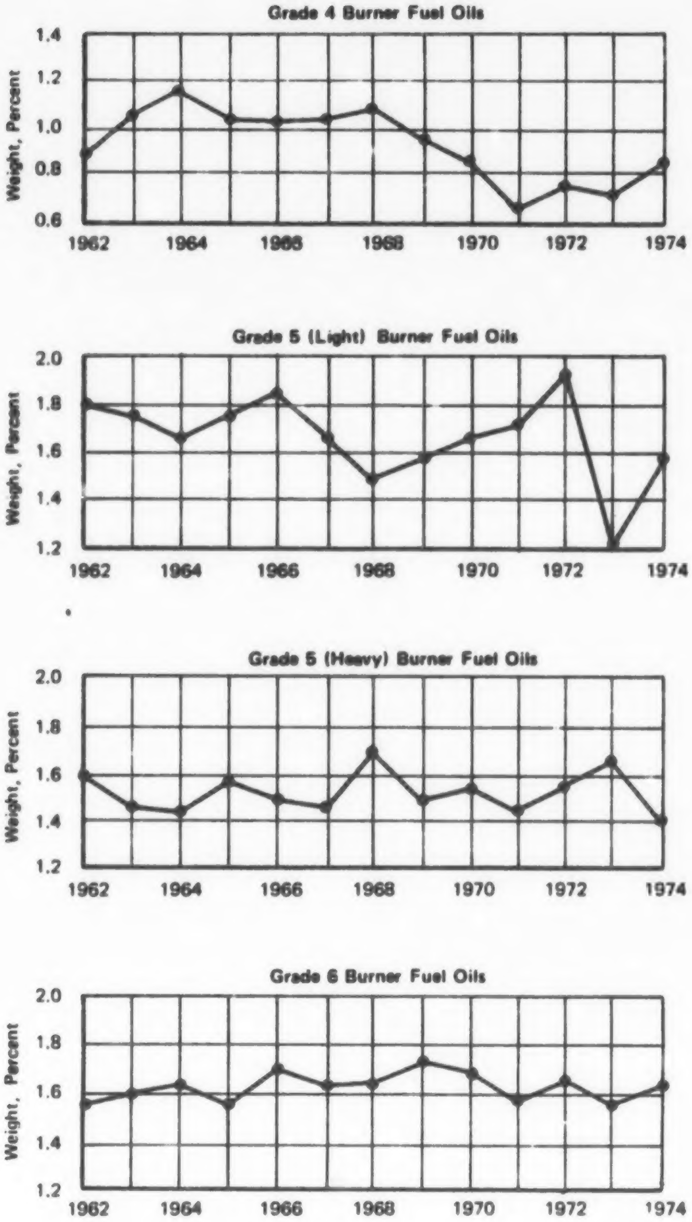
The remainder of this section deals with the sulfur specification of residual fuel oils manufactured and marketed in the U.S. (as distinguished from fuel oils burned within the refinery or imported for domestic sales).

The forecast of the sulfur level of residual fuel oils manufactured and marketed in the U.S. was based upon an analysis of the current air quality regulations required by federal, state, and city agencies; the current status of these regulations, with particular attention to variances being granted; the likely future trend of environmental regulation; and the overall economic environment. In the course of this program, discussions have been held with federal, state, and city environmental protection authorities. A program of interviews with East Coast electric utility companies, accounting for over 90% of the total fuel oil consumed by East Coast utilities, was also conducted.

The current inflationary tendency in the United States and the U.S. policy of energy independence could be contributory factors to the relaxation of air pollution regulations, particularly if the use of domestic coal is to be emphasized. Tendencies to use higher sulfur fuel oils when meteorological conditions are favorable and lower sulfur oils when meteorological conditions are adverse will also play a potential role in the average sulfur level of the fuel oil burned in the U.S. during the next decade. On the other hand, environmental regulations now in effect will not be rapidly changed. Most of the existing variances are temporary and there will still be areas in the United States which are unlikely to grant or renew exemptions.

The historic trend of the sulfur content of heavy fuel oils manufactured and marketed in the United States is shown in Figure 5. It is apparent that the sulfur content of the lighter grade fuel oils has diminished considerably in the last five years. However, the trend of the heavier grade fuel oils is less evident. Table 9 shows the availability of residual fuel oil by sulfur level for the year 1973 and it is apparent that the refinery residual fuel oil production in each of the PAD districts has been at relatively high sulfur levels, between about 1 and 1.5% on average. However, considerable quantities of imported low sulfur oil is marketed, which allows the burning of fuel oil that will meet the statewide sulfur regulations discussed in Appendix D.

Our projections of future sulfur levels for U.S. fuel demand stem from the foregoing discussion and also draw upon more detailed information about likely developments in individual states. From a consideration of such factors it was projected that the sulfur content of the U.S. residual fuel oil demand would be between 1.1 and 1.4%.



Source: U.S. Dept. of Interior, Bureau of Mines, Petroleum Products Survey, Burner Fuel Oils, 1974

FIGURE 5 HISTORIC TREND OF HEAVY FUEL OIL SULFUR CONTENT AS PRODUCED AND MARKETED IN U.S.

Table 9. AVAILABILITY OF RESIDUAL FUEL OIL BY SULFUR LEVEL, 1973

(Thousands of Barrels)

P.A.D. District	Fuel oil source	Sulfur content, wt%				
		0-0.5	0.51-1.00	1.01-2.00	over 2.00	Total
I	Refinery production	11,743	15,834	16,112	8,569	52,258
	imports	232,889	130,258	74,732	160,814	598,912
II	Refinery production	985	30,368	25,952	13,815	71,120
	imports	1,654	1,964	1,719	770	6,107
III	Refinery production	12,790	26,462	9,927	39,276	88,455
	imports	201	2,303	547	1,408	4,459
IV	Refinery products	824	2,451	3,323	3,266	9,864
	Imports	0	0	0	0	0
V	Refinery production	70,348	7,385	47,528	7,639	132,900
	Imports	9,542	32	1,464	221	11,259
U.S. Total	Refinery production	96,690	82,500	102,842	72,565	354,597
	Imports	244,286	134,557	78,860	163,212	620,736

Source: U.S. Dept of Interior, Bureau of Mines, Availability of Heavy Fuel Oils by Sulfur Level, Dec, 1973.

For purposes of this study we assumed an overall U.S. average sulfur content for residual fuel of 1.3 wt.%, representing maximum sulfur levels of 1.4 wt.% east of the Rockies and 0.9 wt.% west of the Rockies. A parametric analysis assumed a U.S. average residual fuel sulfur content of 1.1 wt.%, the weighted average of 1.2 wt.% sulfur east of the Rockies and 0.75 wt.% west of the Rockies.

The importance of testing the sensitivity of study results to the overall U.S. average residual fuel sulfur level is highlighted in Table 10 for the East of Rockies grassroots, Scenario A. It can be seen that the impact on the industry simulation for variations between 1.4% (base case) and 1.2% (parametric run) sulfur level of the East of Rockies residual fuel oil pool is quite marked. As shown in that table, the imported residual fuel oil and the production from existing refineries must be added to the production from new East of Rockies grassroots refineries in 1985 to match the total residual fuel oil sulfur content on the East Coast. Because of the leverage effect of the small volume of residual fuel oil produced from grassroots refineries versus the volume available from imports and existing refineries, the variation in sulfur content of residual fuel oil produced in East of Rockies grassroots refineries is from about 0.6 wt.% to 1.8 wt.% depending upon whether the East of Rockies pool is at 1.2 wt.% or 1.4 wt% (corresponding to overall U.S. pool averages of 1.1 wt.% and 1.3 wt%, respectively). Obviously the cost of desulfurization capability in the grassroots refineries varies accordingly.

Other specifications on the residual fuel oil produced from the U.S. refining industry in addition to the sulfur content were, of course, required. These specifications are summarized in Appendix C.

4. Processing and Blending Routes

The computer simulation of the U.S. refining industry utilized cluster models, chosen to represent the existing refinery structure, and grassroots models, chosen to represent either new grassroots refinery constructions or major expansions of existing refineries. The cluster models were allowed to add new downstream process equipment of reasonable economic size. Accordingly, these models had essentially the same processing and blending capabilities during the study period.

Table 10. GRASSROOTS REFINERY FUEL OIL SULFUR PROJECTION – 1985
SCENARIO A – EAST OF ROCKIES ONLY

Total East-of-Rockies[a]		Imports		Existing refineries[b]		Grassroots refineries[b]	
Sulfur content (wt%)	Fuel oil (MBPD)	Sulfur content (wt%)	Fuel oil (MBPD)	Sulfur content (wt%)	Fuel oil (MB/CD)	Sulfur content (wt%)	Fuel oil (MBPD)
1.2	2,852	1.28	1,797.7	1.44	561.3	0.63	493
1.4	2,852	1.28	1,797.7	1.44	561.3	1.78	493

[a] Fuel oil produced in refineries plus imports

[b] Fuel oil produced and marketed in U.S.

The unit yields and product properties were obtained from a variety of petroleum sources, including the petroleum literature and process licensors. The ability of the cluster models to represent actual refineries when using these unit yields and product properties was confirmed in calibration studies, discussed below. These same unit yields and product properties were also used in the grassroots refinery simulations. A complete discussion of the unit yields and product properties available in the computer program is contained in Appendix H.

Hydrogen generation in the cluster models was obtained solely from refinery gas or imported natural gas. In the grassroots refinery, the first option was also allowed, as well as the ability to generate hydrogen from petroleum naphtha.

Coking capacity for the cluster refineries was maintained at a level similar to that derived during the calibration runs. No coker capacity was allowed to be constructed in the East Coast grassroots refinery, because of market demand considerations. Visbreaking and solvent deasphalting were not allowed in the grassroots models.

In the cluster refineries desulfurization of atmospheric bottoms and vacuum bottoms was not allowed, because the cluster refineries were intended to be descriptive of the current operation of certain existing refineries. In the grassroots refineries, both atmospheric and vacuum bottoms desulfurization were allowed.

The properties of the products from the fluid catalytic cracking (FCC) unit are important to the assessment of the impact of EPA lead regulations since catalytic cracked gasoline represents a significant portion of the gasoline pool. The FCC unit in addition provides feed to the alkylation unit which is a source of high clear octane components. Additional detail on the product properties for the FCC unit as well as the many other units used in the models are discussed in Appendix H.

Another unit critical to the success of a study of motor gasoline properties is the catalytic reforming unit. Table 11 summarizes yields of the Louisiana light naphtha cut at 90, 95 and 100 RON severity reforming and shows the reformate yield loss associated with operating the

Table 11. CATALYTIC REFORMING YIELD DATA
Louisiana crude
(350 PSI separator pressure)

Yield, LV fraction	90 RON	95 RON	100 RON
Propane	.0437	.064	.090
Isobutane	.0192	.027	.035
Normal butane	.0336	.043	.054
Reformate	.8449	.800	.745

unit for a high octane component. A significant amount of effort was expended in the development and confirmation of the yields and properties of this particular unit. Yields for low pressure operation, high pressure operation, and an average operation of reformers across the industry were simulated in detail for several different cases to ensure that the assumptions made in the yield patterns of this critical unit did not significantly detract from the assessment of the impact of the lead additive regulations. A detailed discussion of the reformer evaluations is contained in Appendix H.

Another factor critical to the success of the impact study is the blending octane numbers of reformate, FCC gasoline, etc., for the variety of feedstocks, operating conditions, and gasoline pool compositions used in the study. Because of their importance, blending numbers used in this study were circulated to representatives of the API/NPRA Task Force assisting in the study. In general there was good agreement between the blending numbers utilized in the present study and the suggestions made by members of this task force, as summarized in Table 12. Since any errors in the motor octane number blending characteristics of these streams, in particular, would have a pronounced impact on the results of the study, parametric runs were instituted to determine the result of higher octane numbers required for the unleaded gasoline than 92/84 (RON/MON).

In the model, two distinct hydrogen systems were employed. A high purity hydrogen system was fed by steam-methane reforming and was delivered to high pressure desulfurization and hydrocracking units. The low purity hydrogen system was produced from catalytic reformer units and was distributed to low pressure desulfurization units. Allowances were provided for interchanges from the high purity hydrogen system to the low purity hydrogen system. In addition normal allowances for solution losses and flaring circumstances were also provided. Careful analysis of this hydrogen distribution system indicates that it is a reasonable simulation of refinery systems and will be an adequate description for the purposes of the study. If additional purification of the low purity hydrogen system is required cryogenic units can be added without having a major impact on the overall capital investment penalty associated with the potential regulations.

Table 12. ILLUSTRATIVE BLENDING OCTANE NUMBER COMPARISON
(Clear Motor Octane Number)

Stream	ADL model	Ethyl	DuPont	Marathon	Citgo
90 Sev. reformate	80.1	81-82	82	–	–
100 Sev. reformate	86.0	87-88	87	–	87.1
FCC gasoline (full range)	80.0	80	79-80	82-83	79.9
Alkylate	89.8	–	–	92-93	88.7

5. Calibration of Cluster Models

The U.S. refining industry is composed of nearly 300 individual refineries scattered throughout the country, each characterized by a unique capacity, processing configuration, and product distribution. There are, however, logical regional groupings of major refineries with similar crude supply patterns, processing configurations, and product outputs. Therefore the cluster model approach was developed for this study, in which the existing U.S. refinery industry was simulated by the average operation of three similar refineries located in each of six selected regions. The selection of the three refineries as well as the six selected regions was accomplished with the assistance of the API/NPRA Task Force cooperating in this study. The most important criteria guiding the selection of these cluster models were: (1) each cluster model was to represent, as closely as possible, a realistic mode of operation, in that processing units were to be of normal commercial size and that plants would be allowed normal flexibility in regard to raw material selection and product mix, (2) the cluster model crude slate, processing configurations, and product outputs were to bracket, as best as possible, those variations peculiar to each geographic region.

The final selection of refineries to be represented by the cluster models is shown in Table 13.

PAD District I was simulated by three refineries in the Philadelphia-New Jersey area with capacities ranging from 160,000 to 255,000 bbls/day. PAD District II was characterized by two refinery clusters, one represented by the Large Midwest cluster model simulating the Indiana/Illinois/Kentucky district and processing high sulfur crudes. The Small Midcontinent cluster was also used to represent PAD II, simulating refineries in the Oklahoma/Kansas/Missouri district. This Small Midcontinent model was also used to represent small refiners in PAD Districts other than PAD District II, as described in Appendix G. PAD District III, which represents about 40% of the U.S. refining capacity, was simulated by two models because of its overall importance and because differing types of refinery configurations could be identified. The Texas Gulf cluster was typified by a crude capacity exceeding 300,000 bbls/day and heavy involvement in petrochemicals, lubes and other specialty products. The Louisiana Gulf Coast cluster

Table 13. REFINERIES SIMULATED BY CLUSTER MODELS

PAD district	Cluster identification	Refineries simulated	1973 Crude capacity, MB/CD
I	East Coast	Arco – Philadelphia, Pa.	160.0
		Sun Oil – Marcus Hook Pa.	163.0
		Exxon – Linden, New Jersey	255.0
II	Large Midwest	Mobil – Joliet, Illinois	160.0
		Union – Lemont, Illinois	140.0
		Arco – East Chicago, Illinois	135.0
II	Small Midcontinent	Skelly – El Dorado, Kansas	67.0
		Gulf Oil – Toledo, Ohio	48.8
		Champlin – Enid, Oklahoma	48.0
III	Texas Gulf	Exxon – Baytown, Texas	350.0
		Gulf Oil – Port Arthur, Texas	312.1
		Mobil – Beaumont, Texas	335.0
III	Louisiana Gulf	Gulf Oil – Alliance, La.	174.0
		Shell Oil – Norco, La.	240.0
		Cities Service – Lake Charles, La.	240.0
V	West Coast	Mobil – Torrance, California	123.5
		Arco – Carson, California	165.0
		Socal – El Segundo, California	220.0

represented refineries between 174,000 and 240,000 bbls/day and processed a single source of sweet crude. PAD District V was simulated by a West Coast cluster model and was represented by refineries in the Southern California area. PAD District IV was not explicitly simulated because it represents less than 5% of the total U.S. refining capacity. It was included in the scale up, however, as discussed in Appendix G.

Additional detail on the development of the cluster model concept is contained in Appendix F.

Upon completion of the development of the cluster refinery modeling concept, an extensive calibration effort was undertaken by ADL with the assistance of the Bureau of Mines, Environmental Protection Agency, and the API/NPRA Task Force. A complete discussion of the calibration effort is contained in Appendix I. Only the highlights of this effort will be summarized here.

The annual refining surveys published in the Oil and Gas Journal were used as the basic reference source for determining the cluster model processing configurations, allowing simulation of those refineries listed in Table 13. This source also provided the processing unit capacity available in these cluster refineries, used to limit the available capacity in the cluster models.

The 1973 annual input and output data was furnished by the Bureau of Mines for the aggregate of the three specific refineries comprising each individual cluster model (Table 13). These data included the following: (1) crude oil and other raw materials fed to the refineries, broken down by individual state of origin for domestic crudes and by country of origin for foreign sources; (2) statistics on fuel consumed for all purposes in the refineries; and (3) all petroleum products manufactured by refineries for the year.

Each individual oil company furnished EPA the following proprietary data for 1973: (1) gasoline grade distribution and the associated octane levels and lead levels for each grade, (2) total gasoline volumes and average sulfur contents, (3) crude slates and sulfur levels, and (4) intakes and operating conditions on selected units. The EPA averaged these data to obtain information representing the cluster models, and supplied these data to ADL.

As summarized in Appendix I, four main areas were considered to compare the degree of calibration to the cluster models. These were: (1) overall refinery material balance (i.e., volume of the crude intake required to balance specified product demands and internal fuel requirements), (2) refinery energy consumption, (3) processing configuration, throughputs and operating severities, and (4) key product properties (e.g., gasoline clear pool octanes, lead levels, etc.).

A selected result showing a portion of the calibration results for the Large Midwest cluster is presented in Table 14. Shown here is the crude intake, as specified by the Bureau of Mines data and industry data to provide a given product outturn, as well as a result of the computer model simulation. Also shown is the energy consumption required for this crude intake and product outturn, and a summary of the principle refinery process operations. It is apparent that the agreement of the model prediction and the data base for this Large Midwest cluster is excellent. Additional detail on other clusters as well as other calibration criteria are contained in the discussion of Appendix I.

6. Existing and Grassroots Refineries

The existing U.S. refining industry was simulated by means of the six cluster models, as discussed above. New grassroots capacity was required when atmospheric distillation requirements exceeded 90% of the calendar day capacity listed in the Oil and Gas Journal for the specific refineries being simulated by these cluster models. In practice, operation at 100% of the calendar day capacity cannot be achieved due to unscheduled refinery turnarounds, limitations on secondary processing capacity imposed by product specifications, variations in crude slate, crude supply restrictions, regional and logistical constraints, and imbalances between individual product output and market demand. The industry has historically achieved about 90% of calendar day capacity[14], so this limitation was used to provide a conservative assessment of when new capacity is required, thereby providing a conservative assessment of the penalties associated with the EPA regulation. However, since all penalties are reported as differences between

Table 14. CALIBRATION RESULTS FOR LARGE MIDWEST CLUSTER

		BOM Data	Industry data	Model run
Material balances				
Total crude intake MB/CD		146.1	145.5	145.5
Energy consumption				
Purchased natural gas MB/CD (F.O.E.)		.2	–	.2
Total fuel consumption MB/CD (F.O.E.)[a]		8.1	–	8.4
Electricity MKWH/D		843	–	545
		Oil and gas capacity MB/SD	**Industry data**	**Model run**
Processing summary				
Catalytic reforming	Intake MB/CD	32.7	27.8	27.6
	severity RON	–	90.7	90.0
Catalytic cracking	Intake MB/CD	55.0	51.2	48.7
	conversion % vol.	–	74.9	74.3
Alkylation	Production MB/CD	13.4	11.4	12.0
Coking	Intake MB/CD	15.8	13.6	14.1

[a] Excludes catalyst coke

the various scenarios considered, a precise figure of calendar day utilization is unnecessary.

To meet increased product demand and provide additional crude required to manufacture low lead and unleaded gasoline, an increase in crude run to each cluster is required as the decade proceeds. The existing refining industry (cluster model) is allowed to expand down-stream processing capacity as required to meet these constraints. However, when the crude run reaches the limitation of the atmospheric distillation capacity, the expansion of the cluster model is no longer allowed, and new grassroots facilities must be constructed.

The grassroots models used in this study represent either new, basic grassroots refineries to be built in the United States over the next decade or major expansions in crude distillation capacity in existing refineries.

Those major expansions of existing refining capacity which have taken place within the last few years are often noted by new atmospheric distillation capacity, new tankage requirements, and frequently new or greatly expanded production of refinery products which have otherwise been only a minor component of total product outturn. An example of such major new expansion is the production of large quantities of low sulfur fuel oil. In any event, this type of new major refinery expansion frequently exhibits relatively little interaction with existing refinery processing units, and little additional flexibility for product blending over that of a refinery built on a segregated grassroots basis. Therefore, any requirements for distillation capacity in the industry were simulated by addition of new grassroots capacity. The product outturn and therefore the crude run required for this new grassroots capacity was chosen to be sufficient to balance the product demand and product quality requirements for the United States as a whole. New grassroots construction was simplified by consideration only of a location typified as "east of the Rockies" and another location typified as "west of the Rockies," each location with its own crude slate as discussed in Appendix A.

The yields and product qualities for new capacity additions were identical to those provided in the cluster model operation, with the exception of catalytic reforming, wherein all new capacity was assumed to utilize a yield structure and investment representative of low pressure, bimetallic reformers.

The refinery fuel system for both the cluster models and the grassroots models was constrained to meet environmental regulations typical of the refining regions in which these models operated. A complete discussion of the allowable refinery fuel sulfur level and the methodology by which it was determined is contained in Appendix D.

7. Economic Basis for Study

The estimation of capital investment and operating costs for petroleum processing units is difficult at the present time because of the rapid rate of inflation and the long elapsed time that it takes to build a large and complex petroleum refinery. Investment estimates were obtained by using data from a variety of literature sources, such as the Oil and Gas Journal, and by extensive discussions with process licensors and contractors. In order to minimize the effect of future cost escalations on the cost estimations, the investment estimates were made on a 1975 first quarter basis. This investment estimate will be applicable for refineries which were conceived, designed, equipment ordered, and constructed all within the first quarter of 1975. Escalation of these costs are reported separately in order to allow recalculation of these ultimate investments on other inflation schedules if so desired.

Onsite capital investments were estimated by compositing the information available from these several sources. The onsite process unit estimates used in this study are typified in Table 15. Additional detail of the specific information on capital investments is contained in Appendix H.

The primary purpose of the economic study was to determine the capital investment and operating costs associated with the lead additive regulation under study. Consequently economic penalties for the cluster models were determined by comparing, for example, Scenario B versus Scenario A. Therefore, only the incremental downstream capacity required for Scenario B versus Scenario A was determined and costed. As part of this analysis, charges were assessed for the utilization of spare, idle capacity which was available in 1974 but was incrementally consumed at a faster rate for Scenario B than

Table 15. ONSITE PROCESS UNIT COSTS

Process unit	Size basis, MB/SD	Investment, $/B/SD 1975, 1st quarter
Atmospheric distillation	100	165
Vacuum distillation	40	185
Catalytic cracking	40	925
Catalytic reforming (low pressure)	20	800
Alkylation (product basis)	10	1,400
Isomerization – once through	10	620
Isomerization – recycle	10	1,240
Hydrocracking (high severity)	25	1,400
Naphtha hydrotreating	20	235
FCC/coker gasoline hydrotreating	15	320
Light distillate hydrotreating	30	230
Heavy distillate hydrotreating	30	250
Vacuum gas oil desulfurization (also FCC feed)	25	370
Atmospheric residual desulfurization	50	775
Vacuum residual desulfurization	15	1,500
Coking – delayed	10	930
Hydrogen generation – Methane $/MMSCF/SD	50	230[a]
– Naphtha $/MMSCF/SD	50	260[a]
Sulfur recovery (95% removal) – $/short tons/SD	100	25,000
Sulfur recovery (99.95% removal) – $/short tons/SD	100	50,000

[a] $/MSCF/SD

for Scenario A. Any processing unit severity upgrading that was required was also costed. For example, if the severity of the catalytic reforming unit required was 100 RON in Scenario B but was only 90 RON in Scenario A, then the incremental cost was charged to Scenario B for upgrading this existing catalytic reformer capacity. To determine whether or not the catalytic reformer severity needed to be upgraded, discussions were held with industry sources, who estimated that approximately 25% of the existing catalytic reformer capacity was already capable of 100 RON severity operation. Therefore the remaining 75% of catalytic reformers which were not capable of this mode of operation required an upgrading cost if 100 RON severity were required. Additional discussions of the method of calculation for spare capacity utilization and severity upgrading for all the refinery processing units is contained in Appendix E.

Associated with the onsite costs of incremental downstream capacity in the cluster models is the cost requirement for offsite investment and working capital. As discussed in Appendix E, these costs were taken as a constant 40% of the onsite costs for the cluster models.

For the grassroots models the complete refinery was costed as required for each scenario. For example, the capital cost for the grassroots refinery in Scenario C was then compared to that of Scenario A to determine the incremental costs associated with the lead additive regulations. In this case the onsite process costs were determined in a fashion analogous to that discussed for the cluster model. However, the offsite costs were determined by the Nelson complexity factor approach[17] and a separate assessment of working capital requirements was made, at approximately 70% of the total onsite capital investment. A summary of the items included is shown in Table 16. The net effect of this method of calculation was that offsite and associated costs (including working capital) were approximately 200-300% of onsite costs. For these grassroots refineries the complete onsite plus offsite refinery costs range from about $2900 per barrel per day for a low sulfur crude up to about $3500 per barrel per day for a high sulfur crude, on a 1975 first quarter basis. An illustration of the investment requirements for a grassroots refinery of the present study is shown in Table 17.

Table 16. OFFSITE AND OTHER ASSOCIATED COSTS OF REFINERIES USED IN ESTIMATING COST OF GRASS ROOTS REFINERIES

1st Quarter 1975 Basis
(% onsite cost)

Type of cost	Refinery complexity[a]							
	3	4	5	6	7	8	9	10
Mainly complexity-related offsites, %								
Utilities, safety, fire and chemical handling	61.0	51.4	46.2	41.0	39.2	36.9	35.7	34.0
Buildings	14.0	9.8	8.2	6.6	6.2	5.6	5.2	4.7
Piping, product handling	40.0	26.0	21.4	16.8	15.6	14.1	13.2	12.0
Site preparation, blending, roads and others	23.0	15.8	13.1	10.3	9.4	8.3	7.6	6.7
Subtotal, complexity-related	138.0	103.0	88.9	74.7	70.4	64.9	61.7	57.4
Other offsites, %								
– Includes tankage, ecology and land	87.0	67.0	59.0	51.0	48.0	44.2	42.0	39.0
Total offsites	225.0	170.0	147.9	125.7	118.4	109.1	103.7	96.4
Associated costs								
Chemicals and catalysts	6.0	5.0	4.5	4.0	3.8	3.5	3.3	3.0
Marine or equivalent facilities	20.0	15.5	12.8	10.0	8.8	7.8	6.8	5.8
Working capital	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0
Other	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
– Includes training, spares, autos, telephone, domestic water, cafeteria and recreation								
Total associated	116.0	110.5	107.3	104.0	102.6	101.3	100.1	98.8

[a] See reference #17.

Table 17. GRASS ROOTS REFINERY CAPITAL INVESTMENT

Location:	**East of Rockies**	**Scenario: C**
Crude processed:	**Arabian Light**	
Refinery complexity:	**7.01**	

Process unit	Throughput (MB/SD)	Onsite investment (millions of dollars)
Atmospheric distillation	231.7	28.1
Vacuum distillation	100.1	12.5
Catalytic reforming	52.2	36.5
Catalytic cracking	47.4	42.0
Hydrocracking	26.6	32.2
Isomerization-recycle	11.5	13.8
Alkylation (product basis)	14.9	17.8
Hydrogen manufacture (MMSCF/SD)	62.1	13.3
Desulfurization		
Full range naphtha	62.9	9.4
Straight run distillate	26.4	6.7
Vacuum residue	21.1	27.0
Sulfur recovery and amine treat (short tons/SD)	366	9.4
Total onsite investment		248.7
Offsite and associated costs at 151.0% onsite investment		375.6
Working capital at 70.0% onsite investment		174.1
Total cost		798.4
Investment/B/SD		3,446

Operating costs were determined by a direct assessment, on a unit-by-unit basis, of either the additional downstream processing requirements of the cluster models or the complete refinery requirements for the grassroots models. Catalysts and chemicals, cooling water and electricity were determined from the processing unit intakes themselves and tetraethyl lead was determined as required to meet the gasoline blend requirements. Maintenance and manpower assessments were determined on an off-line basis, i.e., they were not determined by the computer model directly. Manpower requirements were determined both for severity upgrading and for new unit construction by examination of operating requirements of the particular units under consideration. Maintenance costs were assessed at a level of 3% of onsite investments and 1.5% of offsite investments.

In addition a capital charge was assessed for new investment in any processing unit, either in a cluster model or a grassroots model. The capital charge was taken to be 25% of the total capital investment, which is approximately 12% rate of return, on an after tax, discounted cash flow basis. The same capital charge was applied to both the downstream capacity additions in the cluster model and new grassroots facilities in a grassroots model, on the philosophy that the amortization for both types of investments must be approximately equivalent in the present economic climate. A typical level of cash operating expenses (exclusive of capital charge) for the grassroots refinery was approximately 80¢ per barrel of crude capacity.

An assessment of cost escalations over the next decade was made to reflect the actual capital investment which may be required in the time interval in which the actual refinery construction will take place. Such an escalation of costs can result from increases in the costs of refinery equipment which outpace the general inflationary trend in the United States. As a basis for this cost escalation, an approach similar to the usual construction S-curve escalation analysis was conducted, in which the annual escalation for the years 1975-1985 were taken to be 20%, 17%, 15%, 10%, 10%, 10%, 9%, 9%, 8%, 8%, 8%. Clearly, assessments of the rate of cost escalation for the coming decade are highly intuitive and will depend upon a variety of factors, such as further increases in foreign oil prices, general inflationary tendencies in the United States, and many others which are difficult to predict with any degree of precision. Indeed, cost escalation now appears to be flat through 1975. Therefore, the impact of the regulation on the refining industry will be summarized in the following body of the report both on a 1975 first quarter basis and on as escalated basis, with the above assumed escalation schedule.

8. Scale Up to National Capacity

In the cluster model approach, the U.S. refining industry has been simulated by six individual cluster models, each cluster representing three existing refineries in different regions of the United States. To represent the impact on the U.S. refining industry, it is necessary to scale up the results of the cluster model analysis to a regional and a national basis. From this estimate of the total production capability of the existing U.S. refining industry, requirements of the new grassroots models are obtained by subtracting existing capability from the total product demand of the U.S. refining industry. Appendix G discusses the scale up method and the derivation of product demands for grassroots refineries in detail.

The general method employed in scaling up data from the cluster runs to the existing U.S. refining industry is to compare the gasoline outturn of the region being simulated by the cluster model to that of the cluster model itself. For example, the East Coast cluster represents the refineries in PAD District I, so a scale up factor in 1973 of 7.127 is used, since this is the ratio of gasoline production of District I to the gasoline production of the East Coast cluster. However, the cluster model used for PAD I is known to be typical only of the major gasoline producing refineries in that region. Therefore, there is, by definition, a quantity of atypical refining capacity which is not represented by the yields used in the East Coast cluster model. Hence an estimate was made also of the atypical refining capacity in PAD I, to be included as a component of the scale up of the East Coast cluster model results to PAD I.

PAD II is represented by two cluster models. It has been assumed in scale up that the Small Midcontinent cluster represents operations of the Oklahoma/Kansas/Missouri district and that the balance of District II is represented by the Large Midwest cluster. Similarly, in PAD III, it has been assumed that the Louisiana Gulf cluster represents the Louisiana Gulf refining district and the Texas Gulf cluster represents the balance of PAD III.

The West Coast cluster is assumed to represent the operation of PAD V. PAD IV was not represented by a specific cluster model so that the total refining capacity of PAD IV was similarly included as an atypical factor in the scale up analysis.

The results of the application of this scale up method, when composited for the total U.S. refining industry are shown in Table 18 for 1973. Here the crude consumption by the cluster models agrees with the Bureau of Mines data to within about 2% and the total refinery intake agrees to within about 1%.

The major refinery products agree with the Bureau of Mines data within about 5%, with the exception of LPG (which was a swing product in the computer runs) which deviates from the Bureau of Mines data by about 15%. The total product outturn agrees with the Bureau of Mines data to within about 2%. Therefore, it is felt that the model scale up method is calibrated well with the Bureau of Mines data for the purposes of the present study, which emphasizes total energy penalties of the refinery and addresses itself to gasoline production capability. For other types of studies, the scale up method could be further refined, if so desired, to provide a closer match of the other minor products from the refining industry.

Model results for the study years of 1977, 1980, and 1985 were scaled up using the atypical refining concept described above. In 1977 scale up factors were based on meeting gasoline demand for the total U.S. For 1980 and 1985, however, the scale up factor approach was based on total crude run in each cluster and the effective crude oil distillation capacity for the region being simulated by that cluster. The scale up factors used were calculated by making the crude run in each region equal to the effective crude oil distillation capacity for that region, defined as 90% of the calendar day rated capacity.

Table 18. MODEL SCALE-UP COMPARISON, 1973

U.S. total input/output data, thousands of barrels

Refinery intakes/outturns	Cluster model results	Bureau of Mines data	Deviation of model from B.O.M. data (%)
Intakes:			
Crude oil	12,713.6	12,430.7	2.3
Butanes	254.2	219.8	15.6
Natural gasoline	365.2	439.2	16.8
Other	167.6	281.3	–
Total intake	13,500.6	13,371.0	1.0
Outturns:			
LPG	401.2	349.8	14.7
Gasoline	6,572.1	6,572.2	0
Naphtha	227.5	234.7	3.1
BTX	164.5	156.7	5.0
Distillate fuel oil	3,157.9	2,992.8	5.5
Residual fuel oil	956.0	971.5	1.6
Other	1,886.7	1,849.7	–
Total outturn	13,365.9	13,127.4	1.8

As discussed in Appendix B, the import levels of products were held constant at the 1973 level for the coming decade. Therefore, after scaling up of the cluster results, adding atypical factors, and adding import levels, the product outturn from the grassroots refineries could be obtained by difference from the forecast total petroleum products demand. The results showed that by 1980 seven new grassroots refineries would be required in PAD Districts I through IV and two new refineries would be required to meet PAD District V product demands at approximately 200,000 BPD each. By 1985, a total of fifteen new refineries were required for PAD Districts I through IV and a total of three refineries were needed for PAD V.

The utilization of such scaleup factors allowed a direct assessment of the total energy penalties associated with each of the scenarios under discussion, as well as an assessment of the operating costs required to meet the lead additive regulations. However, capital investments were not determined solely by a direct utilization of the scaleup approach, because this approach does not weight sufficiently heavily the capital requirements of the small refineries simulated by the Small Midcontinent cluster. Therefore, an additional factor was utilized in a scaleup for capital costs, as discussed in detail in Appendix G. Such an approach adequately includes the dollar cost to the small refiner as a component of the overall cost to the industry, because his percentage of the total cost is relatively small. However, it does not adequately address the total impact on the small refiner nor the possible impact on the competitive structure of the petroleum industry.

III. STUDY RESULTS

A. BACKGROUND DISCUSSION

There are two promulgated regulations on lead usage addressed in this study (Federal Register, January 10, 1973; December 6, 1973). One requires unleaded gasoline to be available for cars requiring it, i.e., those equipped with catalytic converters for emissions control. The other requires that the use of lead additives in the total gasoline pool (leaded and unleaded combined) be phased down to no more than 0.5 gm/gal by January 1, 1979.

Two external forces, then, are driving the refiner in his usage of lead additives. The phase down regulation places precisely timed limits on total lead usage, although there is still flexibility regarding the quantity of lead the refiner can use in each grade of gasoline. The unleaded gasoline regulation is not nearly so precise, depending upon automobile manufacturers' use and market demand for automobiles equipped with the catalytic converter. The study assumed 2% unleaded gasoline sales prior to the 1975 model year introduction, virtually complete use of the converter starting with the 1975 model year, and a transition to a total gasoline pool consisting solely of unleaded gasoline by 1985.

If lead is removed from gasolines traditionally manufactured in the United States, the resulting gasoline pool would have a research octane number (RON) of approximately 88 and a motor octane number (MON) of about 80. To provide an unleaded gasoline with a minimum RON of 92 and a minimum MON of 84, as required in the present study, the U. S. refining industry must manufacture gasoline with clear (unleaded) octane numbers about four numbers higher than when manufacturing leaded gasoline. The lead phase down schedule will similarly require the manufacture of higher octane gasoline.

Production of those gasoline blending components whose clear octane numbers are highest must therefore be increased. Those hydrocarbons that exhibit high clear octane numbers are either aromatic hydrocarbons (benzene, toluene, etc.) or isoparaffinic hydrocarbons (isooctane, isopentane, etc.). The manufacture of unleaded gasoline can therefore be achieved by increasing the percentage of aromatics in gasoline (sometimes called the aromatic route) or increasing the percentage of isoparaffins in gasoline (sometimes called the aliphatic route) or by a combination of both.

Increased production of aromatic compounds is achieved by operating catalytic reformers at higher severities and building new high severity reformer capacity. However, high severity operation does not yield as much gasoline, so additional crude oil is required to produce a fixed volume of gasoline. An increase in clear RON is not matched by a number for number increase in clear MON, so the clear MON specification becomes limiting. This results in clear RON octane "giveaway", i.e., production of gasoline with a higher clear RON than required to meet minimum RON specifications. Also, the combination of yield loss and the limiting MON specification markedly increases capital investment and operating costs to produce a fixed volume of gasoline. Extraction of reformate to recover aromatics for gasoline blending, analogous to the production of aromatic petrochemicals, is not a satisfactory means of octane enhancement because of the large by-product volumes of low octane raffinate to be disposed of.

Increased production of isoparaffins is achieved by the isomerization of light straight run naphthas (usually containing C_5 and C_6 paraffins) or by alkylation (combining isobutane with propylene and butanes into higher carbon atom isoparaffins).

The detailed results showing processing configurations, gasoline blends, costs, etc., that are required to manufacture unleaded gasoline with and without lead phase down can be found in Appendix J. This study does not attempt to define the impact of the lead phase down regulation alone, without the simultaneous introduction of unleaded gasoline. Instead, the base scenario assumed no lead regulations were imposed (Scenario A); this was then compared to a Scenario B in which only the unleaded gasoline regulation was imposed. Finally, the unleaded gasoline regulation and the phase down regulation were simultaneously imposed (Scenario C) for comparison to Scenario B (unleaded gasoline regulation alone imposed). In general, it is not possible to combine these comparative results to determine the impact of some new combination of these two lead additive regulations which has not been discussed herein.

B. MANUFACTURE OF UNLEADED GASOLINE

1. 1985 Results

Production of 100% unleaded gasoline has been assumed by 1985, at which point Scenarios B and C become identical. In all the cluster models, the processing changes that occurred to produce unleaded gasoline were very similar. Virtually all the light straight run naphtha in the C_5 to 160°F boiling range (containing mainly C_5 and C_6 hydrocarbons) was isomerized either in once-through units or recycle units. Catalytic reformers were operated at the maximum severity of 100 RON allowed in the models and new capacity was also built. Had higher severity reforming been allowed in the model, it is possible that isomerization capacity would have been lower. New alkylation units were built. Hydrocracking units were operated at the same throughput as the base case (Scenario A -- producing leaded gasolines) or in some cases at lower throughput. No new catalytic cracking capacity was built, although some changes in conversion levels occurred.

The composition of the gasoline pool based on model results before and after significant introduction of unleaded gasoline (Scenarios A and B, respectively) is shown in Table 19 for 1985. In all models, Scenario A was required to make 2% of the gasoline pool an unleaded product while in Scenario B the entire pool was unleaded. As a result of the processing changes discussed above, manufacture of 100% unleaded gasoline had a significant effect on the pool composition. None of the models included isomerate in the leaded gasoline pool. In Scenario B, 5 to 13% of total gasoline volume was comprised of isomerate, while alkylate was increased in all models to between 9 and 16% of total volume. Reformer severity was increased to the maximum allowable 100 RON for all existing clusters, and between 96 and 99 RON for the grassroots models. These results indicate that the production of unleaded gasoline was accomplished by a combination of the aromatic and aliphatic routes mentioned earlier. Aromatic hydrocarbons

Table 19. COMPOSITION OF GASOLINE POOL BEFORE AND AFTER INTRODUCTION OF UNLEADED GASOLINE – 1985

	Cluster model												East of Rockies, Grass Roots				West of Rockies	
	East Coast		Large Midwest		Small Midcontinent		Louisiana Gulf		Texas Gulf		West Coast		Sour Crude		Sweet Crude		Grass Roots	
Scenario[a]	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
Isomerate LV%	–	7	–	9	–	13	–	7	–	10	–	7	–	10	–	9	–	5
Reformate – LV%	34	31	30	30	16	22	22	25	30	29	22	26	36	37	47	48	42	40
Alkylate – LV%	9	12	14	16	14	16	14	16	9	12	9	11	10	14	6	9	8	11
Other – LV%	57	50	56	45	70	49	64	52	61	49	69	56	54	39	47	34	50	44
Total	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Reformate severity – RON	92	100	91	100	96	100	90	100	91	100	92	100	90	96	90	97	90	99

[a] Scenario A is the base case (leaded gasoline)
Scenarios B and C are identical in 1985 (100% unleaded gasoline)

were increased by operating catalytic reformers to produce about 100 RON reformate while isoparaffinic components were increased by the introduction of isomerate into the gasoline pool and by blending larger volumes of alkylate.

In all cluster models representing existing refineries, there was a significant reduction in the volume of gasoline produced (between 1.8% and 3.5%) compared with Scenario A. This volume loss is made up by the grass-roots models, as shown in Table 20. Unleaded gasoline was produced at exactly the minimum motor octane specification of 84 in all cases. The research octane number of the unleaded gasoline was always higher than the minimum specification of 92 by 0.8 to 2.0 numbers, depending on the cluster model.

As contained in Appendix J, in the East Coast cluster model, total gasoline production was reduced by 3.5% and the unleaded gasoline was produced at a research octane number which was 1.8 numbers above the minimum specification of 92. New isomerization, alkylation and catalytic reforming capacity additions were required.

In the Large Midwest cluster model, total gasoline production was reduced by 2.5% and the unleaded gasoline was manufactured at a research octane number which was 2.0 numbers above the minimum specification. New isomerization, aklylation and catalytic reforming capacity additions were required.

In the Small Midcontinent cluster model, total gasoline production was reduced by 3.3% and the unleaded gasoline was manufactured at a research octane number which was 0.8 numbers above the minimum specification. New isomerization, alkylation and catalytic reforming capacity additions were required.

In the Texas Gulf cluster model, total gasoline production was reduced by 3.1% and the unleaded gasoline was produced at a research octane number which was 1.2 numbers above the minimum specification. New isomerization, alkylation and catalytic reforming capacity additions were required.

Table 20. TOTAL U.S. GASOLINE PRODUCTION – 1985 (MB/CD)

	Production from existing refineries[a]	Production from grassroots refineries	Total Production
Scenario A	6,587.1	1,453.5	8,040.6
Scenario B[b]	6,407.0	1,633.6	8,040.6
Difference	180.1	(180.1)	0.0

[a] Includes 226.8 MB/CD of gasoline produced from atypical refineries.

[b] Scenarios B and C are identical in 1985 (100% unleaded gasoline).

In the Louisiana Gulf cluster model, total gasoline production was reduced by 3.3% and the unleaded gasoline was manufactured at a research octane number which was 1.6 numbers above the minimum specification. New isomerization and reforming capacity additions were required.

In the West Coast cluster model, total gasoline production was reduced by 1.8% and the unleaded gasoline was produced at a research octane number 1.3 numbers above the minimum specification. New isomerization capacity was required.

The grassroots models were used to make up the loss of gasoline in existing refineries represented by the cluster models. New isomerization, alkylation and catalytic reforming additions were required to manufacture unleaded gasoline and hydrocracking requirements were lower than for Scenario A. Unleaded gasoline was manufactured to a research octane number which was 1.2 numbers above the minimum specification of 92 in the West of the Rockies model and 1.4 numbers higher in the East of the Rockies model.

2. 1980 Results

Before executing the 1980 model runs, certain restrictions were placed on the processing options available in the cluster models. Processing schemes which would be inconsistent with the 1985 results were not allowed. For example, if a cluster model did not build new capacity of a particular process in 1985, it was not allowed to do so in 1980.

Production of unleaded gasoline is approximately 60% of the total gasoline produced in 1980. The processing changes that are required by 1985 to manufacture unleaded gasoline are also required in 1980 but to a lesser extent. Gasoline production is reduced by 0.5% to 1.8% depending on the cluster model. Unleaded gasoline was also manufactured in 1980 to exactly the minimum motor octane specification of 84 but was always above the minimum research octane specification of 92.

In the East Coast cluster model, total gasoline production was reduced by 1.5% and unleaded gasoline research octane was 1.5 numbers above the minimum specification of 92. New isomerization and alkylation capacity additions were required. Catalytic reformers were operated at an average severity of 95.6 RON.

In the Large Midwest cluster model, total gasoline production was reduced by 0.7% and the unleaded gasoline was 2.1 numbers above the minimum specification. New catalytic reforming capacity was required and catalytic reformers were operated at an average severity of 97.5 RON.

In the Small Midcontinent cluster model, total gasoline production was reduced by 1.0% and unleaded gasoline research octane was 0.3 numbers above the minimum specification. New catalytic reforming and alkylation capacity additions were required and catalytic reformers were operated at an average severity of 96.9 RON.

In the Texas Gulf cluster model, the total gasoline production was reduced by 0.5% and unleaded gasoline research octane was 1.1 numbers above the minimum specification. New isomerization and catalytic reforming capacity additions were required and catalytic reformers were operated at a severity of 97.9 RON.

In the Louisiana Gulf cluster, total gasoline production was reduced by 0.6% and the unleaded gasoline research octane was 1.2 numbers above the minimum specification. Catalytic reformers were operated at an average severity of 93.2 RON.

In the West Coast cluster model, total gasoline production was reduced by 1.8% and unleaded gasoline research octane was 0.8 numbers above the minimum specification of 92. New alkylation capacity was required and catalytic reformers were operated at an average severity of 94.2 RON.

As in 1985, the grassroots models were used to make up the loss of gasoline from the cluster models. The grassroots processing configurations in 1980 were similar to those in the 1985 cases.

3. 1977 Results

Production of unleaded gasoline is approximately 30% of the total gasoline pool in 1977. Very little additional processing was required in the cluster models in 1977. Catalytic reformers were operated on average at slightly higher severities (up to 2.9 RON) than in the base case Scenario A. Unleaded gasoline was produced with research octane numbers above the minimum specification of 92 in only the Large Midwest and Texas Gulf cluster models. In all cases, unleaded gasoline exactly met the minimum motor octane specification of 84.

C. INTRODUCTION OF LEAD PHASE DOWN

After determining the requirements to manufacture unleaded gasoline in 1977, 1980, and 1985 the impact of simultaneously reducing the allowable lead levels in leaded gasolines was then studied.

Average lead levels of the total gasoline pool before the introduction of lead phase down (Scenario B) were 1.44 cc/G in 1977 and 1.0 cc/G in 1980.

With lead phase down, the average lead content of the total gasoline produced was controlled to a maximum of 1.0 grams per gallon (g/G) in 1977 and to a maximum of 0.5 grams per gallon in 1980. The model actually contains blending numbers based on cubic centimeters per gallon (cc/G) and maxima were set at 0.94 cc/G and 0.47 cc/G.

The major impact of lead phase down was a significant increase in the need for catalytic reforming capacity and in the severity of catalytic reforming operations in 1977 and 1980. In most cluster models there was a small increase in the requirement for other octane producing processes.

The net effect of lead phase down, then, is to speed up the timing of new processing capacity needs that ultimately would be required for the manufacture of 100% unleaded gasoline by 1985.

D. SUMMARY OF ECONOMIC PENALTIES

The capital investment requirements to manufacture unleaded gasoline, with and without lead phase down, are given in Table 21.

In order to manufacture unleaded gasoline, a capital requirement of 5.7 billion dollars by 1985 (based on first quarter 1975 costs) is noted. This capital requirement includes costs for utilization and upgrading of existing capacity as well as construction of new capacity. An estimate has also been made of the final investment required based on the timing of the investments and forecasted inflation rates, leading to an ultimate capital investment requirement of 14.9 billion dollars by 1985.

Table 21. TOTAL U.S. CAPITAL REQUIREMENTS FOR LEAD ADDITIVE REGULATIONS

(millions of dollars)

	East Coast	Large Midwest	Small Midcontinent	Louisiana Gulf	Texas Gulf	Grassroots East of Rockies	Subtotal PAD I-IV	West Coast	Grassroots West of Rockies	Subtotal PAD V	Total U.S.A.
Unleaded gasoline[a]											
Non-inflated											
(1st qtr 1975 basis)											
1977	–	–	29	–	131	–	160	53	–	53	213
1980	55	351	175	24	482	406	1,493	78	47	125	1,618
1985	394	607	330	465	309	1,265	3,370	388	89	477	3,847
Total	**449**	**958**	**534**	**489**	**922**	**1,671**	**5,023**	**519**	**136**	**655**	**5,678**
Inflated											
1977	–	–	41	–	184	–	225	74	–	74	299
1980	107	686	342	47	942	793	2,917	152	92	244	3,161
1985	1,174	1,808	983	1,385	921	3,768	10,039	1,156	265	1,421	11,460
Total	**1,281**	**2,494**	**1,366**	**1,432**	**2,047**	**4,561**	**13,181**	**1,382**	**357**	**1,739**	**14,920**
Unleaded gasoline with lead phasedown[b]											
Non-inflated											
(1st qtr 1975 basis)											
1977	129	316	45	89	647	–	1,226	132	–	132	1,358
1980	45	(108)	151	151	(292)	374	321	(27)	44	17	338
1985	(174)	(208)	(196)	(240)	(355)	(374)	(1,547)	(105)	(44)	(149)	(1,696)
Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**

[a] Unleaded gasoline relative to total leaded gasoline pool.

[b] Lead phase down with unleaded gasoline relative to unleaded gasoline without lead phase down.

When the phase down of lead additives in the total gasoline pool is superimposed upon the introduction of unleaded gasoline, the effect is to change the schedule of capital investment requirements. In 1977, production of unleaded gasoline would require $0.2 billion; superimposing lead phase down would add an incremental $1.4 billion over Scenario B. By 1980, cumulative investment for unleaded gasoline would be $1.8 billion, and superimposing lead phase down would add an incremental $1.7 billion. By 1985 there is no incremental cumulative penalty over Scenario B for lead phase down, since all gasoline produced is unleaded. The investment credit shown in the 1985 study (noncumulative) reflects the accelerated investment requirement; more investment is required for Scenario C relative to Scenario B in 1977 and less in 1985. Thus, total cumulative investment to manufacture unleaded gasoline will be $5.7 billion by 1985 whether or not lead phase down is introduced. It can therefore be seen that the primary impact of lead phase down is on the timing of capital outlays and not on total cumulative investment.

Table 22 gives a breakdown of the capital requirements in two categories: 44% of the total capital is required for utilization and upgrading of existing capacity and 56% is required for addition of new capacity. Appendix E explains the methodology for estimating these cost elements. Of particular importance in deciding the upgrading costs for catalytic reformers were the assumptions regarding the capability of existing units to operate at high severities. It was assumed that 25% of existing reformers were capable of operating at 100 RON severity and would not require any upgrading costs. This assumption is discussed later in additional detail.

The estimated total economic penalty to the U. S. refining industry for the manufacture of unleaded gasoline is given in Table 23. This indicates a penalty of 1.71 cents per gallon of unleaded gasoline by 1985, on a first quarter 1975 basis. Investment related costs (capital charge) are a significant proportion (70%) of the total cost in 1985. Considering the effect of inflation of construction costs, the ultimate penalty will be higher.

Table 22. BREAKDOWN OF CAPITAL REQUIREMENTS TO MANUFACTURE UNLEADED GASOLINE

millions of dollars (1Q 1975 basis)

	1977		1980		1985		
	No lead phase down[a]	Lead phase down[b]	No lead phase down[a]	Lead phase down[b]	No lead phase down[a]	Lead phase down[b]	Total
Upgrading and utilization of existing capacity	213	1,199	1,067	(302)	1,213	(897)	2,493
New capacity	–	160	551	640	2,634	(800)	3,185
Total	**213**	**1,359**	**1,618**	**338**	**3,847**	**(1,697)**	**5,678**

[a] Unleaded gasoline relative to total leaded gasoline pool.

[b] Lead phase down with unleaded gasoline relative to unleaded gasoline without lead phase down

Table 23. U.S. ECONOMIC PENALTIES TO MANUFACTURE UNLEADED GASOLINE

	Cents per gallon of unleaded gasoline[a] (IQ 1975 basis)		
	1977	1980	1985
Capital charge[b]	0.16	0.70	1.19
Crude oil penalties	0.28	0.41	0.98
LPG credits	(0.06)	(0.27)	(0.25)
Lead credits	(0.28)	(0.46)	(0.52)
Operating costs	0.03	0.23	0.31
Total	0.13	0.61	1.71

[a] Unleaded gasoline relative to total leaded gasoline pool.

[b] 25% of capital investment required.

The economic penalty for the simultaneous introduction of lead phase down is given in Table 24, which indicates a penalty of 0.5 cents per gallon of total gasoline produced in 1977 and 1980. The capital charge used in the derivation of this penalty has been based on the difference in total capital investment requirements for manufacturing unleaded gasoline with and without lead phase down. Of course, by 1985, the additional capital investment that is shown to be required for lead phase down in 1980 will ultimately also be required for the manufacture of unleaded gasoline.

E. SUMMARY OF CRUDE AND ENERGY PENALTIES

The estimated crude oil and energy penalties for the total U. S. refining industry are given in Table 25. For the manufacture of unleaded gasoline, there is an increased crude oil requirement of 255 MB/CD by 1985. This is offset to some extent by the additional production of 93 MB/CD of LPG but there is a final net energy penalty of 180 MB/CD of fuel oil equivalent.

Superimposition of lead phase down increases the crude oil requirements by 74 MB/CD and 55 MB/CD in 1977 and 1980, respectively. It also increases the net energy penalty by 38 MB/CD and 35 MB/CD of fuel oil equivalent in 1977 and 1980, respectively. Since the gasoline pool is 100% unleaded in 1985, there are, of course, no energy penalties for the superimposed lead phase down regulation in comparing Scenario C with Scenario B.

Table 24. TOTAL U.S. ECONOMIC PENALTIES FOR LEAD PHASE DOWN

	Cents per gallon of total gasoline pool[a] (1Q 1975 basis)	
	1977	1980
Capital charge[b]	0.33	0.39
Crude oil penalties	0.34	0.24
LPG credits	(0.15)	(0.08)
Lead credits	(0.11)	(0.10)
Operating costs	0.08	0.07
Total	0.49	0.52

[a] Lead phase down with unleaded gasoline relative to unleaded gasoline without phase down.

[b] 25% of capital investment required.

Table 25. TOTAL U.S. ENERGY PENALTIES FOR LEAD ADDITIVE REGULATIONS

	Unleaded gasoline manufacture[a]			Lead phase down[b]	
	1977	1980	1985	1977	1980
Basis					
Additional crude oil processed MB/CD	19.9	60.1	255.5	73.7	54.6
Additional LPG produced MB/CD	6.0	56.1	92.5	47.7	25.5
Additional purchased power required MKWH/CD	194	1,604	7,347	1,776	1,933
Energy penalty					
10^9 BTU/CD					
Crude oil	110	336	1,430	413	306
LPG	(25)	(225)	(371)	(190)	(102)
Purchased power	2	16	73	18	19
Total – 10^9 BTU/CD	**87**	**127**	**1,132**	**241**	**223**
Total – MB/CD of fuel oil equivalent	**14**	**20**	**180**	**38**	**35**

[a] Unleaded gasoline relative to total leaded gasoline pool.

[b] Lead phase down with unleaded gasoline relative to unleaded gasoline without lead phase down.

IV. SENSITIVITY STUDY RESULTS

A. INCREASED OCTANE REQUIREMENT FOR UNLEADED GASOLINE

As discussed in Section II, some observers have indicated that ultimate octane requirements for unleaded gasoline may be higher than has been assumed in this study. A limited sensitivity analysis examined the impact of manufacturing unleaded gasoline to minimum octane number specifications of 93 RON and 85 MON.

The analysis was based on the West Coast cluster model to represent the effect on PAD V and on the Large Midwest cluster model to represent the effect on PADs I-III, and was done for 1985.

The scaled-up results of the analysis are given in Table 26. These indicate that the capital investment requirements for the total U. S. refining industry increase from 5.7 to 6.9 billion dollars and the economic penalty increases from 1.71 to 2.10 cents per gallon of unleaded gasoline. The impact of increasing the gasoline octane was much greater in the West Coast cluster model than in the Large Midwest cluster model. This significant increase in the PAD V penalties is largely a result of a 9.5% loss of gasoline production in the West Coast cluster model when producing 85 MON unleaded gasoline. This loss of gasoline is assumed to be made up with grassroots capacity which results in a considerable increase in the capital investment requirements and economic penalties.

Sensitivity runs were also completed in these two cluster models with octane specifications of 94 RON and 86 MON. The models experienced great difficulty in being able to produce gasolines to these octane levels. It may be that the processing options available to the model did not have sufficient flexibility to study the manufacture of these higher octane gasolines, although catalytic reforming at a severity of 103 RON was allowed. Should it be necessary in the future to assess the penalty for

Table 26. EFFECT OF MANUFACTURING UNLEADED GASOLINE IN 1985 TO A SPECIFICATION OF 93 RON AND 85 MON[a]

	Base case 92 RON/84 MON			Sensitivity study 93 RON/85 MON		
	PAD I-IV	PAD V	Total	PAD I-IV	PAD V	Total
Capital investment						
Millions dollars (1st qtr 1975 basis)	5,023	655	5,678	5,827	1,058	6,885
Economic penalty						
Cents per gallon of unleaded gasoline	1.76	1.41	1.71	2.09	2.17	2.10

[a] Unleaded gasoline relative to total leaded gasoline pool.

the industry-wide production of unleaded gasoline of 94 RON and 86 MON, further studies of refining industry capabilities should be undertaken.

B. INCREASED GASOLINE DEMAND WITH UNLEADED GASOLINE

Some observers have argued that the necessary use of unleaded gasoline to meet automotive emission standards has led to changes in engine design which provide inferior mileage. This contention has been debated for some time and cannot be resolved here. However, to analyze the impact of such a circumstance, a sensitivity study was carried out in which the unleaded gasoline demand in 1985 was increased by 5% over the baseline projection. The base case assumed a total ex-refinery gasoline demand of 8014 MB/CD in 1985 and the sensitivity study increased this demand to 8427 MB/CD.

The results of the sensitivity study are shown in Table 27. Capital investment requirements increase from 5.7 to 7.1 billion dollars. The additional cost to manufacture unleaded gasoline increases from 1.71 cents per gallon to 2.08 cents per gallon of unleaded gasoline. The additional manufacturing costs of utilizing unleaded gasoline would be 3.4 cents per gallon of gasoline if the increased crude oil requirements to meet the 5% increase in gasoline demand were taken into account.

C. LOWER GASOLINE GROWTH RATE

The demand growth assumptions used in this study are based on a 2% annual growth rate of all petroleum products from 1975 to 1985. This sensitivity analysis examined the effect of assuming a lower demand growth rate of 1.5% per annum for gasoline, resulting, for example, from the further penetration into the automotive market of smaller cars with better mileage.

The results of the sensitivity analysis showed a reduction in the 1985 total capital investment requirements to manufacture unleaded gasoline of only 70 million dollars (IQ 1975 basis).

D. IMPORTED CRUDE OIL TYPE

The grassroots model for the East of the Rockies simulation in 1985 was run with 100% sour crude oil (Arabian Light) and 100% sweet crude

Table 27. EFFECT OF A POSSIBLE INCREASE IN GASOLINE DEMAND

	Base case	Sensitivity study
Ex-refinery gasoline demand[a]		
MB/CD	8,041	8,427
Capital investment[b]		
Millions dollars (1st qtr 1975 basis)	5,678	7,109
Economic penalty[b]		
Cents per gallon of unleaded gasoline	1.71	2.08[c]

[a] Includes 226.8 MB/CD of gasoline produced from atypical refineries.

[b] Unleaded gasoline relative to total leaded gasoline pool.

[c] Becomes 3.4 cents with increased crude oil to meet incremental gasoline demand.

oil (Nigerian/Algerian mix). The results of the base study assumed that one-third of new refineries East of the Rockies would be sweet crude oil refineries and two-thirds would be sour crude oil refineries.

As a result of the sensitivity analysis, it can be concluded that assuming 100% sweet or sour crude oil has no significant effect on the penalties estimated.

E. TARGET RESIDUAL FUEL OIL SULFUR LEVELS

The base study assumed that by 1985 residual fuel oils from U.S. refineries would meet maximum sulfur levels of 1.4 wt. % in the East of the Rockies model and 0.9 wt. % in the West of the Rockies model. The grassroots refinery models were used to balance both fuel oil volume and fuel oil sulfur level. Only a small change in the assumptions with regard to sulfur levels in total U.S. residual fuel oil production would have a significant impact on the sulfur level required of residual fuel oil in the grassroots models (see Table 10). This is because of the leverage effect of the small volume of residual fuel oil produced in the grassroots models compared to the total U.S. residual fuel oil production.

A sensitivity analysis examined the impact of meeting maximum sulfur levels of total residual fuel oil production of 1.2 wt. % East of the Rockies and 0.75 wt. % West of the Rockies. There was no significant change in the penalties for manufacturing unleaded gasoline.

V. DISCUSSION

Of the cumulative capital requirement by 1985 for the manufacture of unleaded gasoline, some 40% or 2.3 billion dollars was needed for upgrading the severity of existing process units. In turn, this severity upgrading cost is principally the cost of upgrading catalytic reformers to operate at 100 RON severity. In calculating the capital investment for reformer upgrading, it was estimated that 75% of existing catalytic reformers were not capable of low pressure operation at 100 RON severity, and that the capital investment required to upgrade these units is equivalent to the cost of building a new high pressure catalytic reformer (Appendix E). This assessment was based on discussions with industry sources. In practice, the cost of upgrading existing reformers will vary widely, depending upon the constraints of each individual refinery. Since this upgrading cost is so large relative to the total impact of lead removal, more definition is needed of this severity upgrading issue to assess fully the impact on the U. S. refining industry. It is felt that the capital investment estimates made in this study for severity upgrading have a degree of uncertainty that is not contained in the estimates for the building of new process capacity. A closer examination of the severity upgrading issue could increase or decrease the estimated 2.3 billion dollars by 30%.

With the assumed lead phase down schedule, there will be a significant impact on the severity at which catalytic reformers must operate by 1977. To determine the number and size of new capital construction projects required to meet the lead phase down regulations will similarly require a more detailed assessment of the catalytic reforming upgrading issue.

One of the key assumptions in simulating the gasoline producing capabilities of existing refineries is the motor octane blending numbers of the components contained in gasolines. In practice, the blending numbers are inherent to the particular processing configurations and gasoline blend composition in any particular refinery. As discussed in Section II, the blending numbers used in this study were based on a concensus of blending number values from different sources. In retrospect, it is felt that the clear motor octane numbers assumed for catalytic reformate are very slightly on the low side and therefore the penalties assessed in this study should be considered to be conservative.

The simulation of the small refiner has not been covered in great depth in this study. An adjustment was made to the penalties calculated to take account of the higher costs the small refiner would face because of economies of scale, but no allowances were made for restricted blending capability. The small refiner represents a sufficiently small fraction of refining capacity that any understatement of his costs will not affect the overall conclusions. However, it should be pointed out that the small refiner would incur much higher relative penalties than indicated in this study, which could have a significant impact on his competitive position in the industry.

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